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Evaluation of Firemain Architectures and Supporting Reflexive Technology

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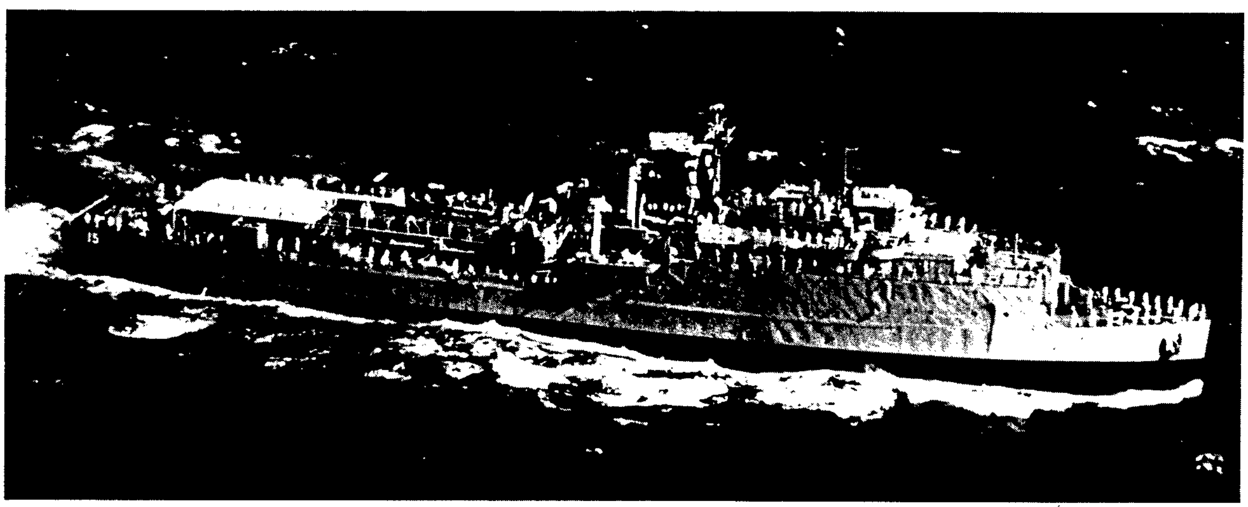

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13. ABSTRACT *(Maximum 200 words)*

The evaluation of conceptual firemain architectures and supporting technology is discussed for the development of a shipboard fluid system which responds reflexively to damage. A comparison of offset loop, dual main and zonal firemain architectures is provided along with results of steady state hydraulic analyses of ruptures. An evaluation of simplified valve segregation logic sequences is discussed, and results of a technology study of sensors, communication methods, sequences is discussed, and results of a technology study of sensors, communication methods, valve and actuators are included. Trade-offs are evaluated to determine the focus of continuing investigation. Ongoing work includes the development of a reliable smart valve which can detect and isolate a rupture, development of a benchtop model to test communication methods and segregation logic sequences and evaluation of applications to other fluid systems.

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Evaluation of Firemain Architectures and Supporting Reflexive Technology

1.0 Summary

The objective of the Damage Control Automation for Reduced Manning (DC-ARM) reflexive fluid system research is to develop and demonstrate the design of fluid systems which respond reflexively to shipboard damage. A reflexive fluid system is one which responds automatically to restore system service following rupture damage or other fault conditions without the need for manned response or information from a higher level control system. This report addresses the evaluation of the conceptual architecture for a reflexive firemain system. The evaluation consisted of performing hydraulic analyses of different firemain architectures, evaluating various logic and segregation sequences following a rupture and surveying technology related to key components.

Hydraulic analyses and survivability evaluations were performed for offset loop, dual main, and zonal firemain architectures. The offset loop design consists of a port main and starboard main offset at different elevations with cross-connections at the forward and aft ends. The dual main design consists of port and starboard mains that are offset but without interconnections. The zonal design consists of a separate loop within each fire zone. These firemain architectures are illustrated in Figures 1, 2, and 3. The results of the analysis indicate that the offset loop design contains the fewest number of pumps and the greatest number of smart valves[1] compared to the other designs. Conversely, the zonal design contains the greatest number of pumps and fewest number of smart valves. The dual main design contains more pumps and fewer smart valves than the offset loop design.

These results indicate that development of a reliable, cost-effective smart valve is a key requirement for achieving reflexive fluid system implementation. With such a valve, survivability of firemain supply to vital loads can be optimized without using an excessive number of pumps (which are relatively more expensive to install and maintain than a valve).

The evaluation of the logic and segregation sequences compared several options for smart valve logic. The logic options included low pressure, hydraulic resistance, flow inventory and rupture signal detection. Low pressure logic closes the smart valve on low pressure. Hydraulic resistance logic closes the valve on low hydraulic resistance[2]. Flow inventory logic closes the valve when the flow balance is not maintained. Rupture signal detection logic closes the valve when a signal traveling

[1] A smart valve contains onboard sensing, calculation and communication capabilities. A smart valve can operate automatically based on the conditions evaluated.

[2] Hydraulic resistance, as used in this report, is defined as the downstream pressure divided by the square of the flow rate.

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down the pipe (pressure, acoustic, vibration or some combination of frequency logic and pressure) indicates that a rupture has occurred. Low pressure logic is considered to be the simplest for reflexive firemain system development because communication between components is not used. The disadvantages of low pressure logic are the inability to detect small ruptures (ruptures of branch piping less than half the diameter of the firemain piping) and the potential to isolate flow to intact sections of piping. Hydraulic resistance logic can locate the rupture path, but additional investigation is needed to determine the sensitivity to small ruptures and the extent of device communication needed. Flow inventory logic, in theory, can detect small and large ruptures since it is based on a "first principle" detection method. However, flow inventory logic can become complicated for some piping configurations and following smart valve failures. Continuing investigation is evaluating combinations of logic methods to determine the optimal performance and simplicity.

The technology study evaluated commercial sensors, device communication methods and valves/actuators applicable to the development of a reflexive fluid system. The results indicate that commercial technology is available to implement reflexive firemain capabilities. However, an evaluation of the use of existing commercial technology with current shipboard maintenance practices has not been performed to determine if the affordability and performance requirements for reduced manning can be met. Industry experience indicates that affordable sensors can provide accurate measurements if appropriate design and installation practices are used, but degradation mechanisms will reduce the accuracy over time and typical calibration practices may not correct the errors. As a result, the development of self-diagnostic and compensating capabilities is needed. These capabilities should include identifying and correcting bias due to fouling buildup on the inside surface of piping and non-ideal velocity profiles which are typical for shipboard fluid systems.

Development of a conceptual smart valve design is underway. This development includes determining sensor specifications, demonstrating communication methods and developing methods to embed sensors and communication methods in a valve. Development of a benchtop model for testing of communication methods and segregation logic sequences is underway. The testing and supporting transient hydraulic analysis will establish the performance capability and limitations of a reflexive system with smart valves. To support this evaluation, transient analysis of the runout of a firemain pump following a rupture is being performed to establish timing sequences of valves and pumps. Plans to test the performance and reliability of potential reflexive system technology on the ex-USS SHADWELL (LSD-15) are under development. This development recognizes that maintenance is a driver of shipboard manning. Therefore, reflexive system designs which use the minimum number of components and proven commercial technology are preferred to more complicated and unproven designs.

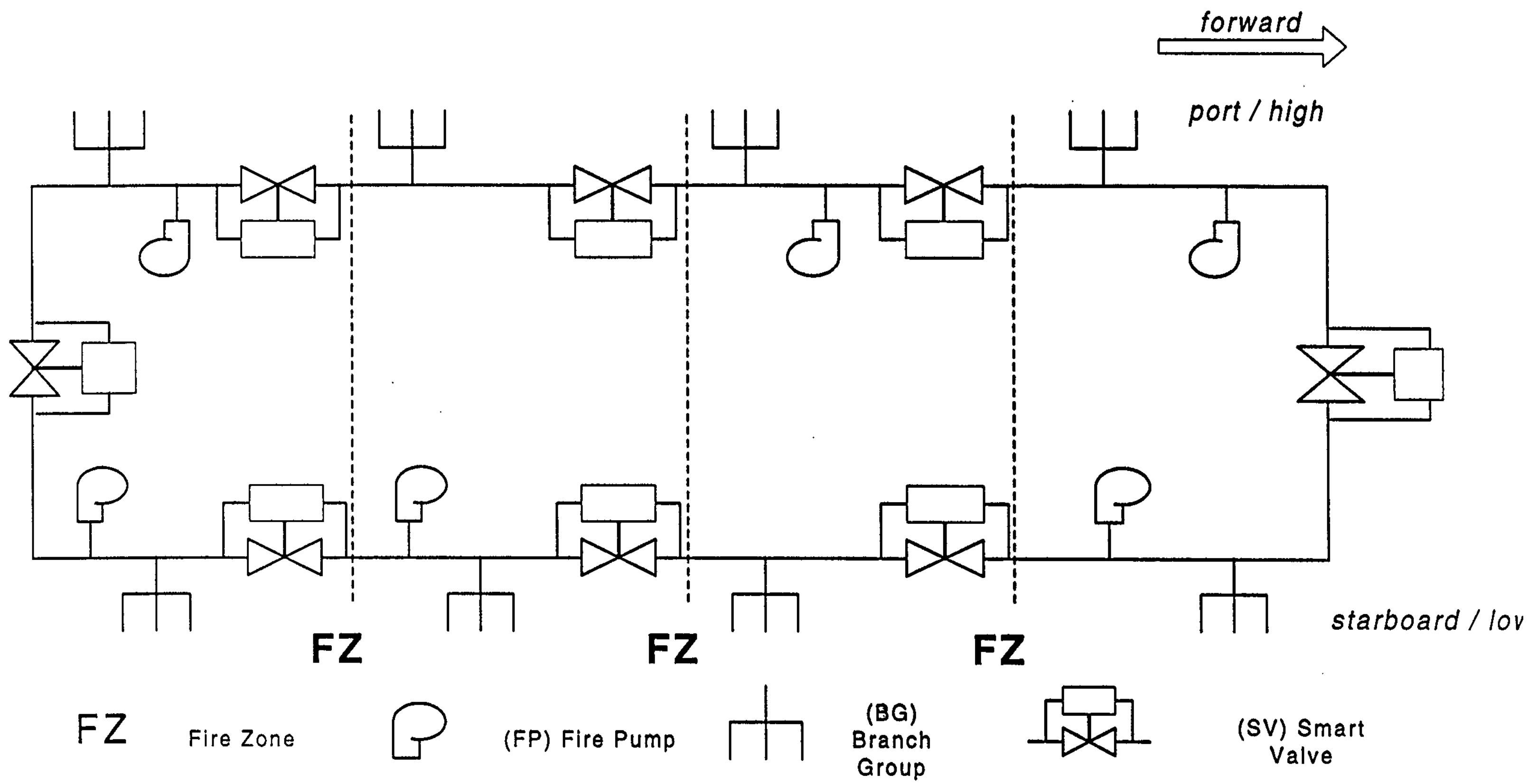


Figure 1. Offset Loop Architecture

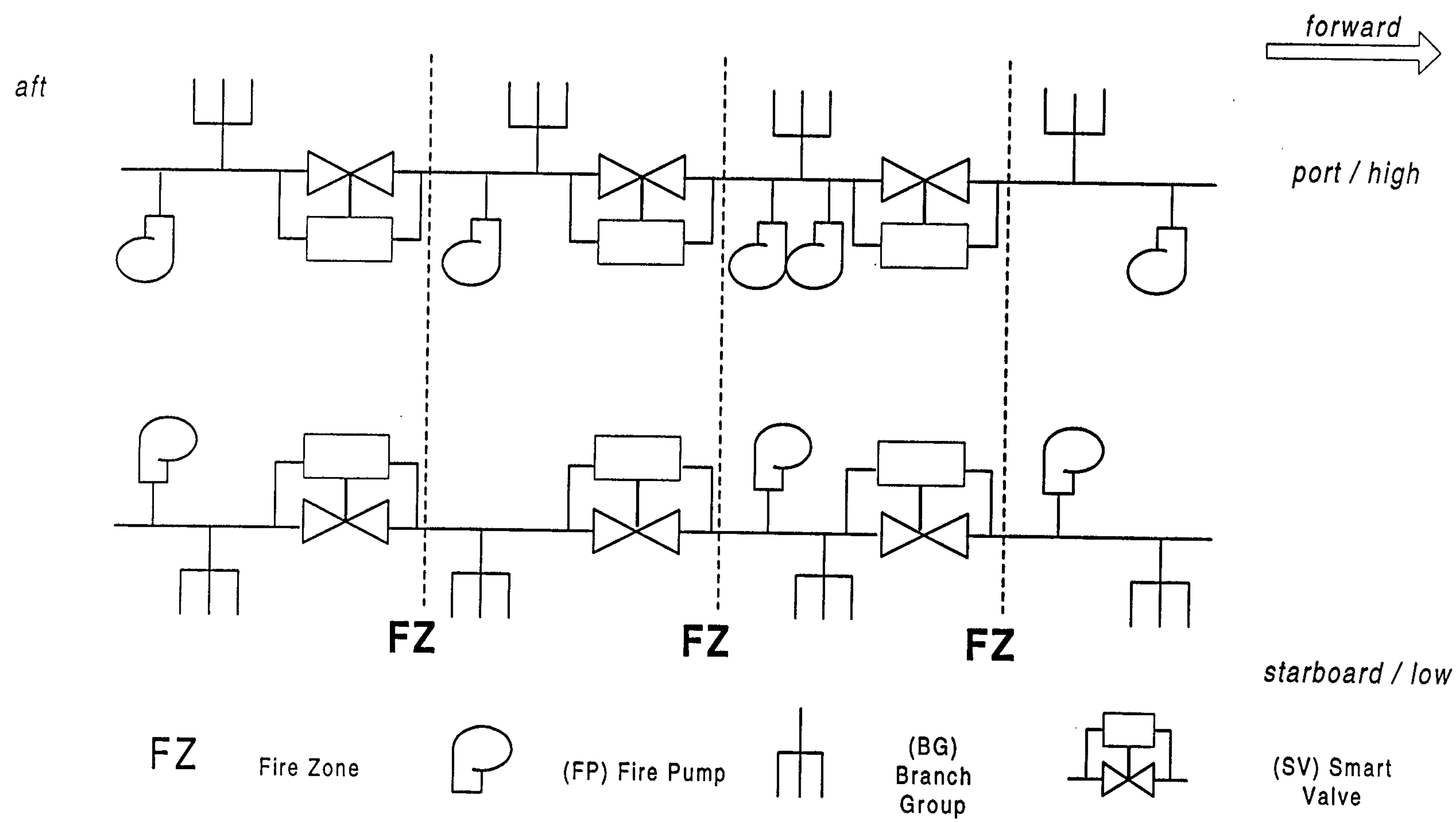


Figure 2. Dual Main Architecture

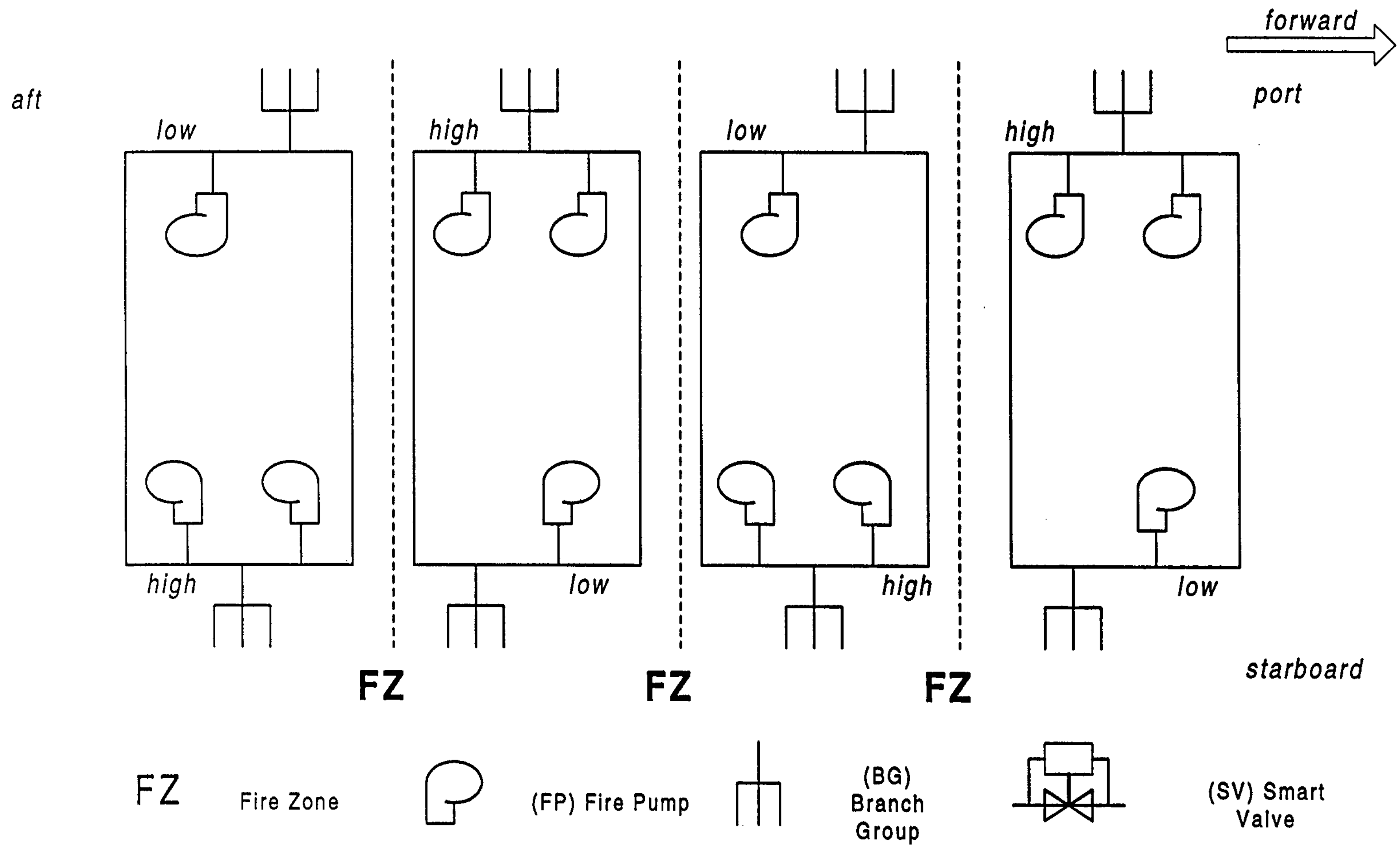


Figure 3. Zonal Architecture

2.0 Introduction

The overall objectives of the Shipboard Damage Control Automation for Reduced Manning project (DC-ARM) are to:

- significantly reduce the manning required for damage control,
- significantly reduce the time to execute effective damage control actions, and
- provide a high degree of survivability in a manner which will be affordable for installation in Navy ships.

To meet these objectives, development of fluid system technology which can automatically respond to fluid system damage is underway. A reflexive fluid system is one which isolates damaged portions of the system and restores intact sections to service without manned intervention. The overall approach for reflexive fluid system development is to design and demonstrate fluid system operation following damage based on affordable commercial technology. System survivability is maximized by automatically isolating damaged portions using local information only. The use of global information such as pre-hit information from a supervisory control system may enhance system reliability and response time but is not considered necessary for adequate system operation.

3.0 Approach

The overall goal of developing a reflexive fluid system is to demonstrate the operation of the components and logic sequences which respond automatically to fluid system damage. This report contains evaluations of firemain architectures, hydraulic analyses to characterize the firemain's response to damage, evaluations of sequences to segregate damaged sections and assessments of commercial technology.

An evaluation of firemain architectures and associated hydraulic analyses were performed for three conceptual designs: offset loop, dual main and zonal. These three designs were considered representative of piping design practices and shipboard damage control practices. Other designs are possible but these designs are sufficient to identify technology and design practices for a reflexive firemain system. The evaluation determined the number of pumps and smart valves required along with the range of pressures and flow rates for various normal operating and damage conditions. Detailed multibranch analyses of complete system designs were not performed; rather, steady state analyses based on simplified equivalent piping networks were used. The results of the hydraulic analyses are the first step in determining thresholds for pressure and flow measurements needed to identify and locate a rupture.

Using the results of the hydraulic analyses, a screening evaluation was performed of segregation sequences to restore a firemain following damage. The segregation or logic sequences considered were low pressure, hydraulic resistance, flow inventory and rupture signal detection. These sequences are based on information which is transmitted in fluid in the pipe, i.e., pressure and flow rate. Other segregation logic may be used (such as methods which interrogate the integrity of the pipe wall and/or methods which assess the damage in the neighborhood of the piping system), but the logic sequences evaluated represent the foundation for rupture detection by a reflexive system. Based on the advantages and disadvantages of each method, effort can be focused on the most suitable segregation methods that warrant additional evaluation.

A technology study was performed to determine suitable commercial sensors, device level communication methods and valves/actuators for reflexive system development. The objective of the technology study was to identify cost effective and reliable technologies which could be used to demonstrate a reflexive fluid system aboard a ship built in the near future. Based on this objective, the study focused on established and proven technology, but developing and unproven technologies may be considered as needed.

Based on the results of these three evaluations, a trade-off comparison of reflexive system technologies was performed to determine the most suitable method of continuing development. The overall approach is shown in Figure 4.

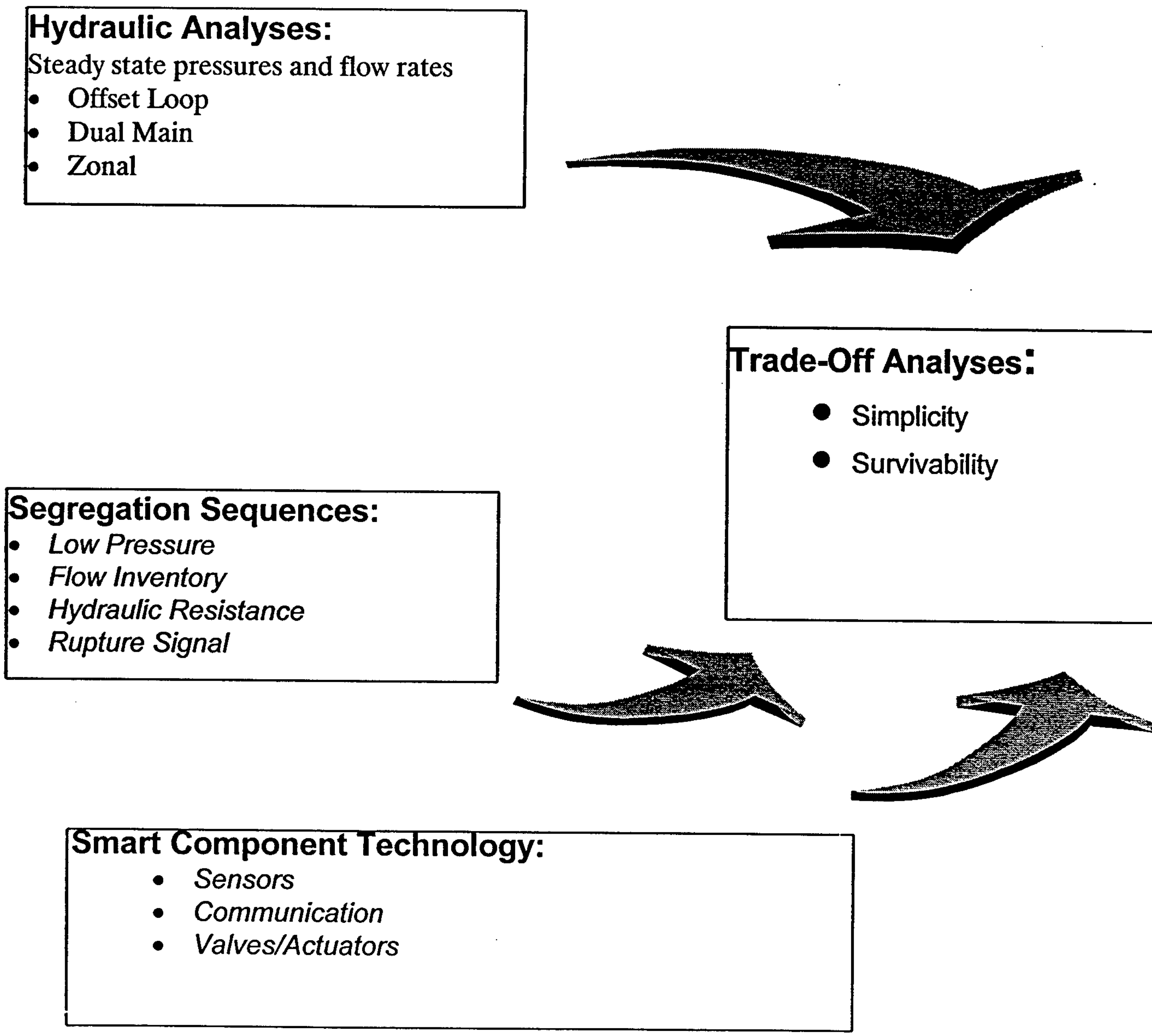


Figure 4. Schematic of Approach for Reflexive Fluid System Development

4.0 Results and Discussion

4.1 Firemain Architectures and Hydraulic Analysis

4.1.1 Candidate Architectures

Three candidate architectures for the firemain system configuration are considered: offset loop, dual main and zonal. Other configurations are possible, but these architectures are considered representative of current models of survivable piping systems. The evaluation of these architectures is simplified using a consistent set of assumptions:

- Four fire zones
- Ship is 400 ft. (122 m) long with each fire zone 100 ft. (30.5 m) long
- One branch group[3] off the firemain on each side of the ship within each fire zone
- One fire pump in each fire zone. If necessary, additional pumps will be added to provide the needed capacity,
- Smart valves located to ensure flow can be isolated between adjacent fire zones and such that only one smart valve is damaged following a casualty and
- Single weapon hit. The damage extends (1) longitudinally for a length of 60 ft. (18 m), (2) transversely over to the firemain on the opposite side of the hit, but not damaging the firemain on the opposite side of the ship and (3) vertically for three decks, i.e., 3/4 of the depth of the ship.

The number of pumps is determined by estimating the flow requirements for a typical firemain:

1. Normal Operation. Only services required for normal, undamaged conditions are accounted for.
2. Missile Hit with a Chemical/Biological/Radiological (CBR) weapon (so that countermeasure washdown is needed). The missile hit is located in the second fire zone from the front of the ship at a high elevation. No damage to the firemain is incurred. The firemain remains intact.
3. Mine hit located forward and low. No damage to the firemain is incurred. The firemain remains intact.
4. Main Machinery Space Fire. Fire is located low, mid to aft of the ship. The firemain remains intact.
5. Missile Hit with a Chemical/Biological/Radiological (CBR) weapon (so that countermeasure washdown is needed). The missile hit is

[3] A branch group is a set of firemain services (such as sprinkling, hose reels and AFFF) which joins the firemain in a single pipe connection. Appendix A contains the branch groups considered for this analysis.

located in the second fire zone from the front of the ship at a high elevation. One pump, one smart valve, one branch group and one segement of the firemain pipe are lost to the damage.
6. Mine hit located forward and low. A double-ended rupture of the firemain is suffered. One pump, smart valve and branch group are lost to the damage.

It is assumed that one pump is out service at any time (prior to damage) and the maximum pump flow rate is 1550 gpm (5867 lpm) consistent with the assumptions in [1] for pump runout[4]. The results of the evaluation of flow requirements are provided in Appendix A.

Based on the assumptions discussed above, the configurations for the three architectures are shown in Figures 5 to 7. An actual firemain design may contain additional valves and branch piping, but the conceptual designs shown are sufficient for this evaluation. The three conceptual designs for the fire main are evaluated based on the following criteria:

- Simplicity. Simplicity is determined by the number of pumps and key valves and by the number of alignments required to support different operating conditions (such as normal operating and battle-ready). In general, a design is simple if it contains few components and few operating alignments since the number of potential fault conditions is minimized.

- Survivability. Survivability is determined by the number of intact branch groups supplied by the firemain following a casualty, continued supply to intact vital loads and capability to maintain firemain supply to all fire zones following a casualty. In general, a highly survivable design relies on redundant components which are separated and require minimal communication with neighboring or remote equipment.

The results of the evaluation are summarized in Table 1 and discussed below:

[4] Pump runout is a condition where the pump operates against little system resistance with maximum flow.

Table 1
Summary of Comparison of Firemain Architectures

Evaluation Criterion	Offset Loop	Dual Main	Zonal
Number of Pumps	6	8	12
Number of Smart Valves	8	6	0
Number of Branch Groups Available After Casualty	6	6	6
Flow Available in Each Fire Zone Following Rupture?	No[1]	Yes	No[1]
Restrictions for Vital Load Piping Arrangement?	Yes[2]	Yes[2]	Yes[2]

Notes:

1. **For the offset loop, firemain is lost in the forward or aft fire zone if the cross connect valve is damaged. For the zonal arrangement, firemain is lost in the same fire zone where damage occurs.**
2. **For the offset loop, supply to vital loads is assured if redundant supplies are provided from two firemain locations separated by two smart valves. For the dual main, supply to vital loads is assured if redundant supplies are provided from each main. For the zonal arrangement, supply to vital loads is assured if redundant supplies are provided from adjacent fire zones. In addition to these redundant piping paths, flow restrictions or smart valves in the supply piping may be needed to ensure that two segregations of the firemain are not lost if the supply piping is damaged.**

The offset loop architecture shown in Figure 5 consists of two mains joined by two cross connections: one port side located at a low elevation and one starboard side located at a high elevation. It should be noted, however, that the ZEBRA condition (closed valves in cross connections) will not be used for this evaluation. Otherwise, the offset loop architecture would resemble and behave as a dual main architecture, which is described below. Smart valves are located such that after isolation of a rupture, the firemain would continue to provide flow to six of the intact branch groups. Six pumps are required to meet the flow demands which is the least of the three architectures evaluated. Eight smart valves; one near the boundary of each fire zone on each main and one in each cross connection are needed to restore service to 6 of 8 branch groups following rupture. The primary vulnerability of the offset loop is smart valve malfunction since at least two smart valves must close to restore firemain pressure to one segment. If reliable smart valve operation can be demonstrated, an offset loop design would be the most cost effective firemain architecture.

The dual main architecture shown in Figure 6 is characterized by two separate mains, one port side located low in the ship and one starboard side located high in the ship. Each main operates independently, with a separate set of pumps to satisfy flow demands. There are no cross connections between the firemains; however, redundant supplies from each main may be provided to vital loads. As with the offset loop, smart valves are located so that isolation of a rupture in the firemain would continue to provide flow to six of the intact branch groups. There are six smart valves total; one near the border of each fire zone on each main. The principle advantage of the dual main design is that firemain is available to all fire zones following a rupture without smart valve operation. The vulnerabilities of the dual main design are (1) the potential loss of both mains if cross-connected piping for a vital load ruptures, and (2) the potential loss of two fire pumps which supply a main.

The zonal architecture shown in Figure 7 consists of four separate flow loops, each within a different fire zone. Each loop is comprised of two mains, one high in the ship and one low with cross-connects between the two. The high and low mains alternate sides (port or starboard) of the ship from fire zone to fire zone. This alternating configuration will minimize the probability that two neighboring loops are damaged by a weapon hit at the same time. There are no smart valves in the zonal architecture. If one loop is lost to a weapon hit, the six intact branch groups in the other fire zones would still provide flow. The principle advantage of the zonal design is that no smart valves are required to maintain 6 out of 8 branch groups. The principle vulnerabilities of the zonal design are (1) the loss of all firemain within a fire zone following a rupture, and (2) the potential loss of firemain for two fire zones depending upon the layout of the piping. With these vulnerabilities, routing of numerous supply paths across fire zone boundaries and implementing separation criteria for piping in adjacent fire zones may be needed. Developing and implementing a survivable zonal design is considered to be difficult based on these vulnerabilities.

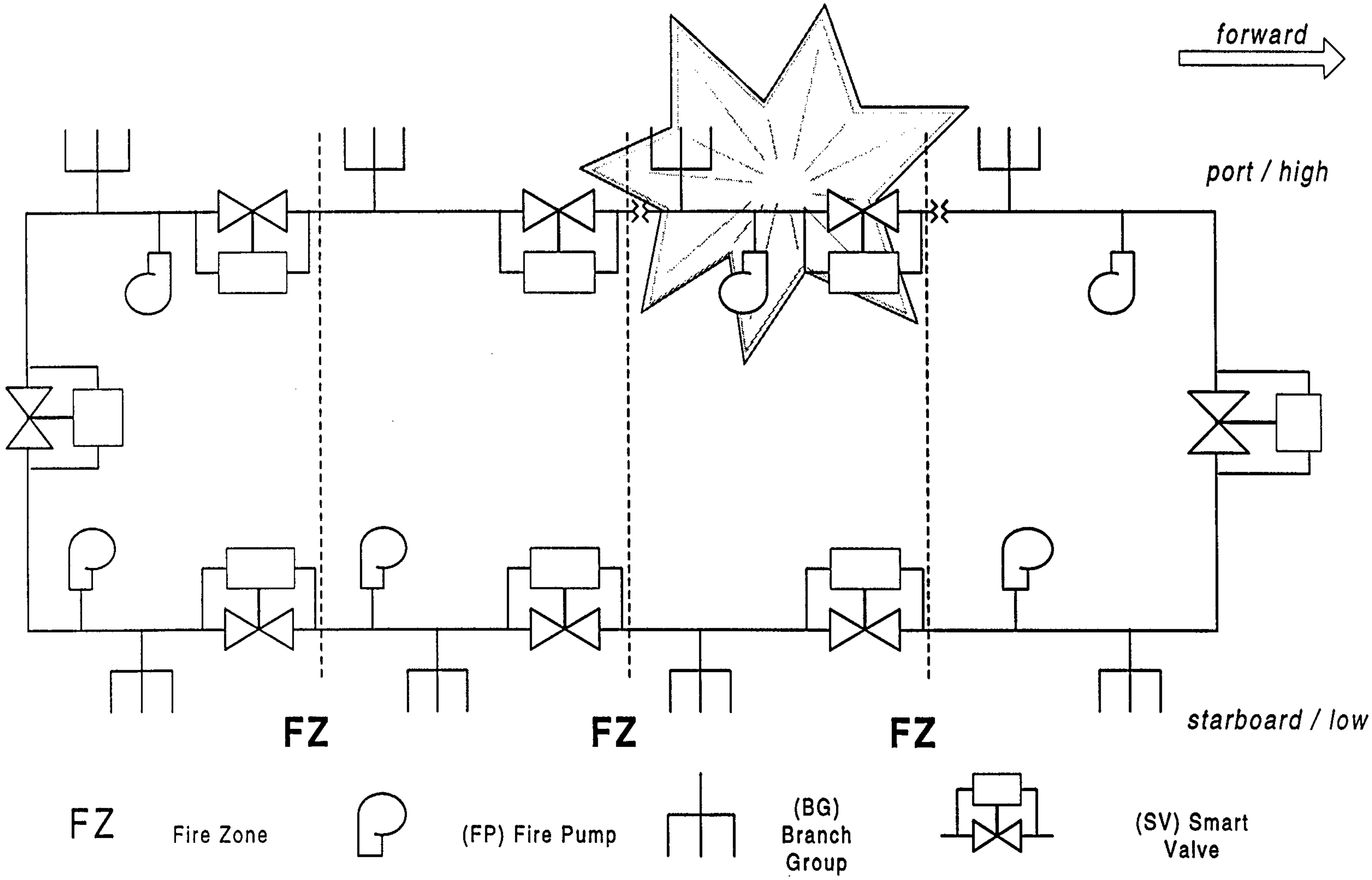


Figure 5. Offset Loop Architecture With Blast Damage

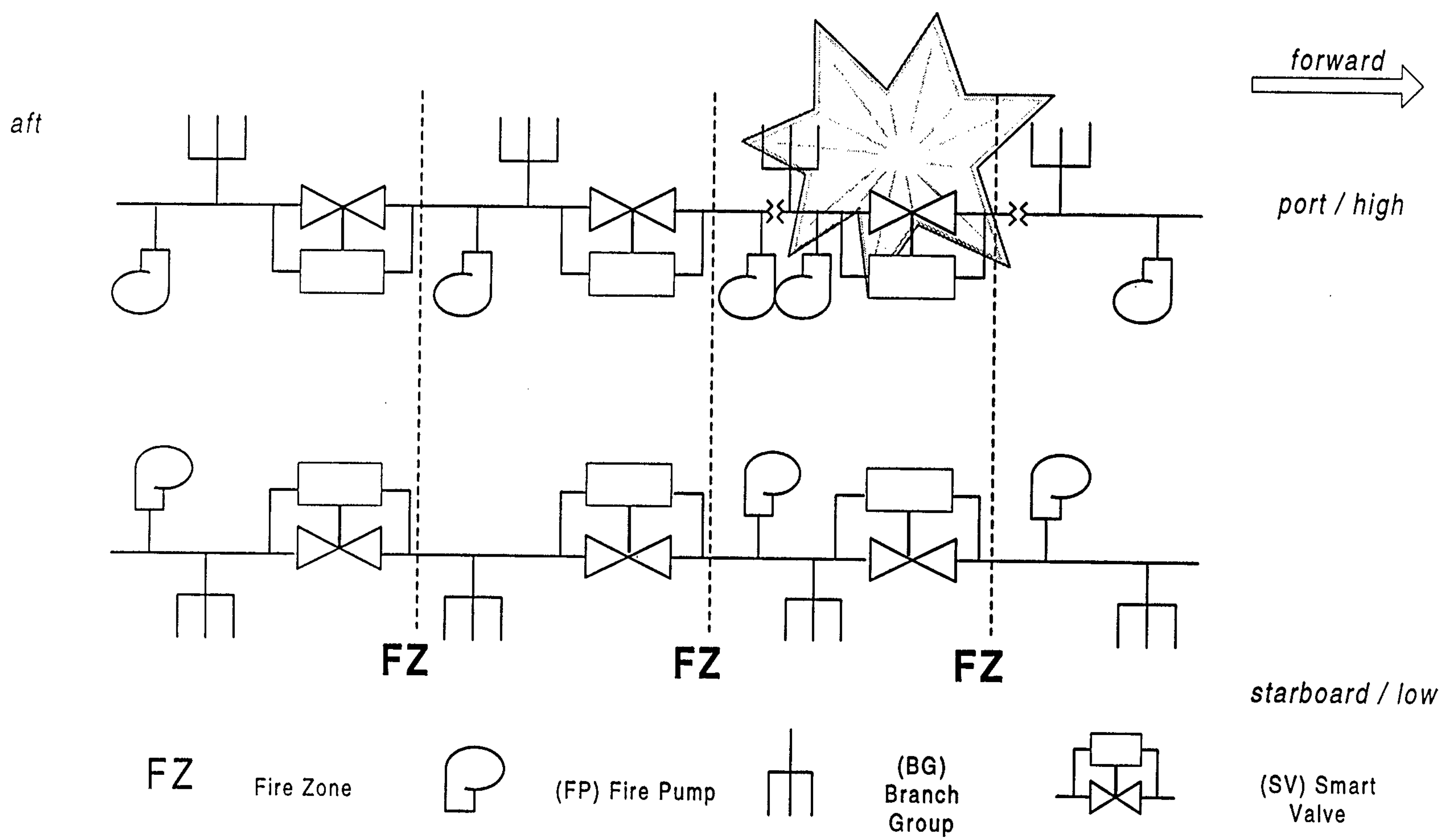


Figure 6. Dual Main Architecture With Blast Damage

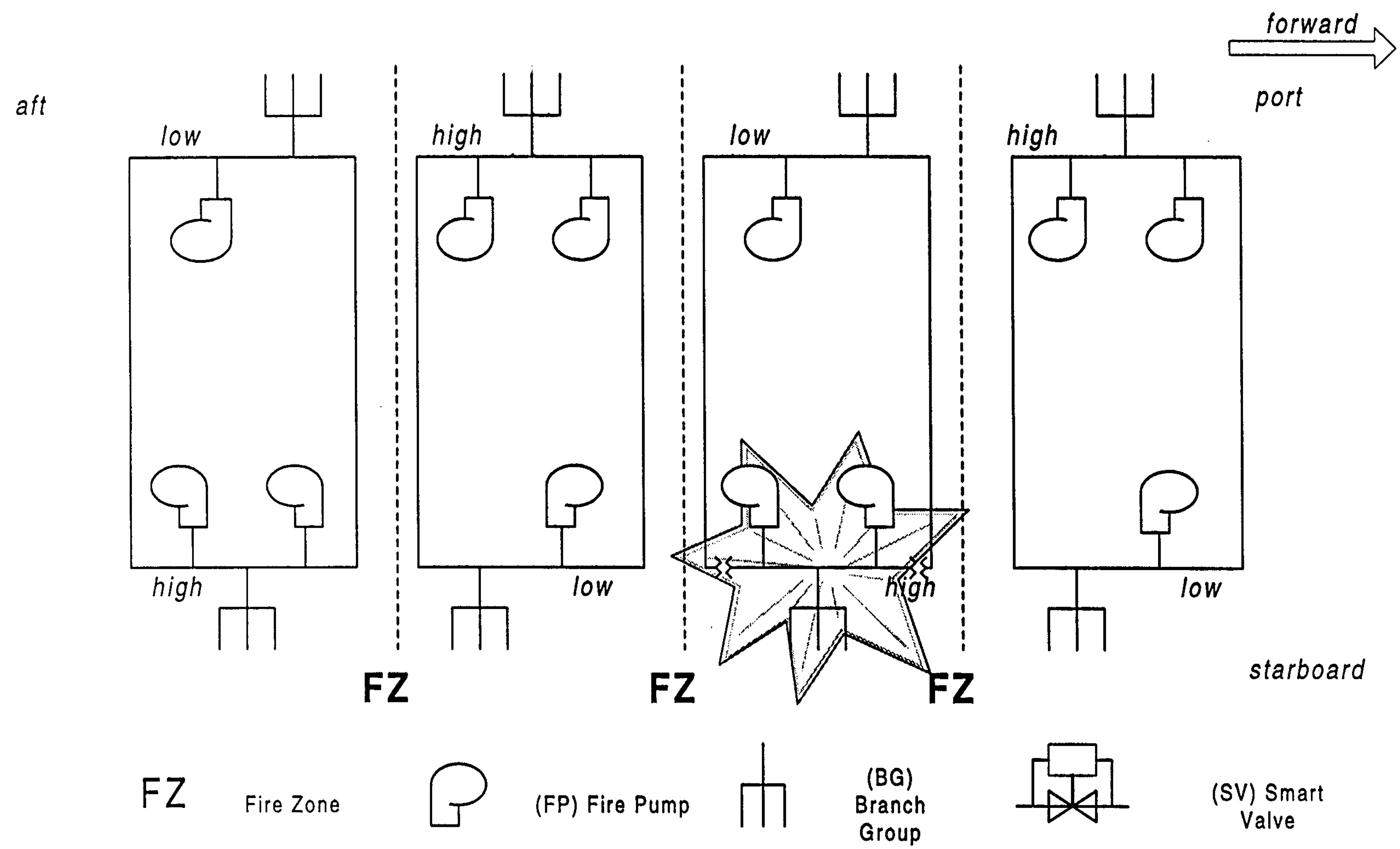


Figure 7. Zonal Architecture With Blast Damage

4.1.2 Hydraulic Analysis

A detailed hydraulic analysis of the candidate architectures was performed using the software AFT Fathom, Version 3.0 [2]. AFT Fathom is a steady state pipe flow analysis application. The cases described in Section 4.1.1 have been analyzed:

1. Normal Operation
2. Missile hit with Chemical, Biological or Radiological (CBR) weapon. No firemain rupture
3. Mine hit. No firemain rupture
4. Main machinery space fire
5. Missile hit with Chemical, Biological or Radiological (CBR). Double ended rupture of the firemain
6. Mine hit. Double ended rupture of the firemain

Cases that model damage to the firemain (5 and 6) are evaluated with all valves open (i.e., the rupture is not isolated). The model for each architecture that was analyzed using the software is documented in [3]. The results of the analysis using the AFT Fathom software are summarized in Table 2 and are shown graphically in Appendix B. For all architectures, when there is a large rupture in the fluid system (cases 5 and 6), the pressure drops to virtually zero psig near the rupture, pressure drops dramatically in the rest of the system, the required flow to services cannot be met and all pumps operate at or near their runout flow rate.

The results of the hydraulic analysis indicate that (1) pressures following a large rupture are at least 100 psig less than normal pressures, (2) firemain flow rates following a rupture may be approximately the same as normal flow demands following a casualty and (3) hydraulic conditions following a rupture are similar to conditions following a pump trip[5] or runout. Due to the similarity between hydraulic conditions following a rupture and other events where the piping remains intact, the potential for inadvertent closure of smart valves based on hydraulic data only may be significant.

[5] A pump trip is a condition where the pump stops without warning due to malfunction or equipment safeguards.

Table 2
Summary of Hydraulic Analysis Results
Range of Firemain Flow Rates and Pressures

Evaluation Case	Firemain Pressures and Flow Rates (see note)		
	Offset Loop	Dual Main	Zonal
Normal Operation (Case 1)	173 – 181 psig (1193-1248 kPa) 2.5 - 9.5 gpm (9.5 – 36 lpm)	Not Evaluated	Not Evaluated
Missile Hit w/ CBR (Case 2)	111 – 126 psig (765 – 869 kPa) 29 – 1794 gpm (110 – 6790 lpm)	123 – 156 psig (848 – 1075 kPa) 12 – 811 gpm (45 – 3070 lpm)	101 – 177 psig (696 – 1220 kPa) 12 – 2370 gpm (45 – 8970 lpm)
Mine Hit (Case 3)	134 - 142 psig (924 – 979 kPa) 380 - 1250 gpm (1438 – 4731 lpm)	106 – 172 psig (731 – 1186 kPa) 12 – 1290 gpm (45 – 4883 lpm)	96 – 180 psig (662 – 1241 kPa) 0 – 1537 gpm (0 – 5818 lpm)
Main Machinery Space Fire (Case 4)	132 - 140 psig (910 – 965 kPa) 37 – 419 gpm (140 – 1586 lpm)	Not Evaluated	Not Evaluated
Missile Hit w/ CBR Firemain Damage (Case 5)	0 – 39 psig (0 – 269 kPa) 685 – 3067 gpm (2593 – 11609 lpm)	0 – 156 psig (0 – 1075 kPa) 12 – 2573 gpm (45 – 9739 lpm)	0 – 177 psig (0- 1220 kPa) 12 – 2370 gpm (45 – 8970 lpm)
Mine Hit w/ Firemain Damage (Case 6)	0 – 42 psig (0 – 290 kPa) 100 – 3107 gpm (379 – 11760 lpm)	0 – 147 psig (0 – 1013 kPa) 855 – 3129 gpm (3236 – 11843 lpm)	0 – 181 psig (0 – 1248 kPa) 0 – 1770 gpm (0 – 6699 lpm)

Note: The pressure data shown is the range of firemain pressures at the smart valves. For the zonal architecture (which does not have smart valves), the pressure data shown is at the branch group connection. The flow data shown is the range of firemain flow rates through the smart valves. For the zonal architecture, the flow rates are for the branch groups.

4.2 Segregation Sequences/Reflexive Valve Logic

Based on the results of the hydraulic analysis and comparison of architectures, an analysis of segregation logic was performed. The purpose of the analysis is to identify the most reliable, cost effective methods which can be used to detect, locate and isolate ruptures. The following segregation methods were evaluated:

- low pressure
- flow inventory

- hydraulic resistance
- rupture signal detection

These segregation methods are simple conceptual approaches based on proven sensor technology which uses fluid transport data (pressure and flow) or data transmitted along the pipe and fluid columns (vibration and acoustic energy). Other leak detection and isolation methods are possible. For example, leak detection methods based on combinations of the above methods or methods which assess the integrity of the pipe wall can be used. A summary of a few pipeline leak detection methods is provided in [4]. Segregation methods considered in this analysis are sufficient to benchmark advantages and disadvantages of simple approaches.

The evaluation performed is based on the offset loop architecture with the following sequence of events before and after a rupture:

1. Firemain system is in ready status with all smart valves open. One or more pumps are operating and one pump is out of service. Large service demands such as countermeasure washdown and magazine sprinkling may or may not be in use.
2. Following rupture, all available pumps start on low pressure.
3. Smart valves evaluate data and change position as needed to isolate the rupture.

Specific timing of the sequencing of pump starts and valve closures is beyond the scope of this report. However, it is assumed current shipboard technology (with pump starts within one minute and valve closures within 30 seconds) is sufficient to restore firemain before the fire spreads to adjacent compartments.

4.2.1 Low Pressure

With low pressure logic, the system is considered to be faulted when the pressure of the system is low. Since the typical firemain pressures are greater than 120 psig and the maximum calculated firemain pressure following a rupture is 30 psig, low pressure is a simple and robust indicator of a fault condition for the firemain. Based on our evaluation, the following are the limitations of low pressure logic:

- Operation Under Non-Rupture Conditions. In addition to rupture conditions, pressure is low when portions of the system are under maintenance and repair and following a pump trip (with one pump operating). As a result, valves may close without a rupture. These inadvertent valve closures may isolate flow to operating services once pumps are restored.
- Isolation of Intact Sections. During a rupture, pressure may be less than 30 psig for all portions of the firemain and therefore all valves may close and isolate intact sections. If a pump is not operating between two closed valves, flow will be starved to services in operation.
- Small Ruptures. Pressure may not be reduced for small rupture conditions. In particular, ruptures of small diameter piping (less than half the diameter of main

piping) or small holes in a larger pipe may not increase flow enough to cause pump runout. Pressure remains high, flow to services is adequate, but the rupture is not detected. Rupture flow rates up to 1500 gpm may not trigger low pressure logic sequences. If detection of a small rupture is desired, logic other than low pressure is needed.

- Inability to Locate Rupture. While low pressure logic can detect fault conditions, additional information is needed to locate and assess the scope of the rupture damage (i.e., which services are affected).

Since low pressure logic is simple, additional investigation of this method is warranted. In particular, methods to eliminate or mitigate the consequences of the limitations discussed above should be evaluated. The use of other logic and control methods in addition to low pressure logic may be one practical approach to consider.

4.2.2 Flow Inventory

Flow inventory logic consists of summing supply and demand flow rates into sections of the system to determine if mass is conserved. If the residual flow rate (i.e., difference between the supply and demand flow rates) is greater than a set point limit, a rupture exists. A simple approach to establish the set point is based on uncertainty of the measurements needed to establish a flow balance. The flow balance between two smart valve segregations is given by:

$$r_Q = \sum_{i=1}^{N} Q_i \qquad (1)$$

where r_Q = flow balance residual between smart valves, gpm (lpm)
Q_i = flow rate in one pipe segment, gpm (lpm)

The uncertainty in the flow balance measurement based on traditional root-sum-squares approach, in [5], is given by:

$$\delta Q_{Total} = [\sum_{i}^{N} \delta Q_i^{\,2}]^{1/2} \qquad (2)$$

where δQ_i = uncertainty in flow measurement of one instrument

If the setpoint is selected as the uncertainty limit, the size of a detectable rupture is based on the number of branches within a firemain section and the accuracy of each flow measurement. The evaluation is complicated by the possibility of failure/damage to smart valves and flow measurement equipment. Under such circumstances, alternate logic is needed such as performing a flow balance on a larger firemain section and using a default flow rate for branch instruments which have failed. It can be seen that the application of this method of rupture detection involves a tradeoff between costs of the instrument and calibration, the size of the rupture which can be detected and the reliability of the detection logic.

As an example, consider a firemain segregation bounded by two smart valves, one fire pump, and 10 firemain services. Flow measurements are made at each smart valve, in the pump discharge header and in each service branch. (The services may be grouped onto one or more branch pipes, but the rupture evaluation is simplified if flowmeters are considered for each branch since flow combinations do not need to be considered.) For the flow measurements at the smart valves and in pump discharge headers, an uncertainty of ±50 gpm (±190 lpm) is assumed based on 5% accuracy for a nominal 1000 gpm (±3785 lpm) flowrate. For flow measurements in the branches, an average uncertainty of ±20 gpm (±76 lpm) is assumed which is greater than 5% of the flow rate for fire plugs but is less than 5% of the flow rate for high flow demands such as countermeasure washdown. Using equation (2) above, the uncertainty of the flow balance is estimated for the following scenarios:

- No Flow Measurement Failure. For the baseline case, the uncertainty of the flow balance is estimated to be ±107 gpm (±405 lpm). Therefore, leaks less than 107 gpm are not detected.
- Smart Valve Failure. If a smart valve fails, a flow balance is assessed by expanding the boundaries to include two neighboring smart valve segregations. Using the flow measurements from two smart valves, two pumps, and 20 branches, the uncertainty is ±134 gpm (±507 lpm). Therefore, leaks less than 134 gpm are not detected.
- Branch Flow Measurement Failure. If flow measurement in a branch fails, default logic is needed to assess the flow balance. Human or machine supervisory input may be needed to increase the reliability of default logic selected. For instance, default logic may consist of using the most recent flow measurement available. With this logic, a rupture is detected if branch flow increases. As a result, initiating any firefighting demand may result in rupture detection and system isolation.

Flow inventory is a "first principle" method of locating a leak and therefore additional investigation of this method is warranted. Investigation of the reliability of the method should be performed considering equipment malfunction and various pipe configurations.

4.2.3 Hydraulic Resistance

Hydraulic resistance logic consists of determining if the smart valve is in the rupture flow path by calculating the hydraulic resistance. Hydraulic resistance is defined for this investigation as follows:

$$R_H = {P_D}/{Q^2} \qquad (3)$$

where R_H = hydraulic resistance, psi/gpm²
P_D = downstream pressure, psig
Q = flow rate, gpm

Following a rupture, flow rate along the rupture path increases while the pressure decreases resulting in a substantial decrease in hydraulic resistance. During normal operation, pressure remains high even through flow rate may increase when a service load is started. Following fault conditions without a rupture (such as a pump trip), pressure decreases and flow decreases such that the hydraulic resistance does not change. Table 3 contains the hydraulic resistance values for some typical scenarios which result in a change of flow rate and pressure.

Table 3
Typical Hydraulic Resistances at
Smart Valve Locations in an Offset Loop Design

Firemain Flow Scenario	R_H Before Flow Change psig/gpm^2 (Pa/lpm^2)	R_H After Flow Change psig/gpm^2 (Pa/lpm^2)
Normal Operation Before Flow Change, Rupture After Flow Change	2 to ∞ (9.6x10^2 to ∞)	$<9.1\text{x}10^{-7}$ ($<4.4\text{x}10^{-4}$)
Normal Operation Before Flow Change, Magazine Sprinkling After Flow Change	2 to ∞ (9.6x10^2 to ∞)	$>4.7\text{x}10^{-5}$ ($>2.3\text{x}10^{-2}$)
Normal Operation Before Flow Change, Pump Trip After Flow Change	2 to ∞ (9.6x10^2 to ∞)	Indeterminate
Countermeasure Washdown (CMWD) Before Flow Change, Rupture After Flow Change	$>3.5\text{x}10^{-5}$ ($>1.7\text{x}10^{-2}$)	$<9.1\text{x}10^{-7}$ ($<4.4\text{x}10^{-4}$)

This data indicates that the hydraulic resistance varies over a very wide range during normal operation, but the resistance following a rupture is less than the normal operating values. Based on the data in Table 3, the hydraulic resistance following a rupture is less than 3% of the resistance of an intact firemain. Therefore, hydraulic resistance may be a reliable indicator of a firemain rupture. The logic would need to distinguish between low flow conditions (such as during normal operation and following a pump trip), high flow non-rupture conditions (such as during CMWD or magazine sprinkling operation) and rupture conditions. Thresholds for each of these hydraulic conditions would need to be established to implement this logic.

Since hydraulic resistance logic can detect the rupture path, additional investigation is warranted to determine requirements for flow and pressure measurements. One method to implement hydraulic resistance logic is to identify conditions where pressure is decreasing and flow is increasing. Suitable thresholds for pressure decrease and flow increase should be identified and evaluated.

4.2.3 Rupture Signal Detection

Rupture signals are pressure and flow data which can be distinguished from other hydraulic transients (such as valve opening/closing, pump starts and waterhammer). Evaluation criteria include rate of change of flow and rate of change of pressure. These criteria include both hydraulic energy variations (with time periods from about 1 to 5 seconds) and acoustic energy variations (with time periods less than a fraction of a second).

In general, data currently available is insufficient to characterize ruptures and normal transients for typical shipboard fluid systems. Traditional development of hydraulic transient analysis [4, 6], has been used to perform detailed simulations of unsteady flow phenomena in pipelines. However, such simulations are complicated due to the number of boundary conditions and component performance data which must be included.

A conclusion of the feasibility of this option is not possible with the data available. The current plan is to measure rupture pressure and flow data from live fire tests and compare the results with scoping transient analyses. The test and analysis results should determine the feasibility to detect a rupture in shipboard fluid systems using rupture signal logic.

4.3 Technology Study

Currently, Hull, Mechanical & Electrical (HM&E) fluid systems on Navy ships use little or no automation. Remote manual operation is provided for a few key components such as valves at primary watertight divisions and pumps. Automated valve operation is provided for actuation of a few selected services (such as magazine sprinkling) or continuous control of fluid temperatures and flow rate (such as for refrigeration pressure and lube oil temperature). In general, very few sensors with remote indication are provided on current HM&E fluid systems. Local pressure gages and temperature indication is common. During normal operation, monitoring by ship personnel is not required since automated operation is inherent in the system designs. During system realignments and abnormal conditions, effort by ship personnel is needed to confirm that the fluid system operation has been adequately restored.

Based on the results of the hydraulic analysis, the comparison of segregation logic sequences, and the status of current technology used in Navy HM&E systems, the technology needed for reflexive firemain system development consists of sensors, valves/actuators and communication methods. Implementation of reflexive designs will require the addition of this technology to fluid systems. The technology added must not increase the maintenance burden of ship personnel. To meet this objective, reliability is a primary criterion for technology implementation and methods to implement self diagnostics should be considered. This section summarizes the status of the commercial development of sensor, communication and valve/actuator technologies and identifies areas of needed development for reflexive fluid systems. The focus of the discussion is on the reliability and maintenance burden associated with implementing new technology on ships.

4.3.1 Sensors

To implement low pressure, hydraulic resistance and flow inventory segregation sequences, pressure and flow measurements are needed. For rupture signal detection, high speed pressure and pipe vibration are considered. For this study, the status of sensor technology is reviewed for pressure and flow measurements only since these measurements are the basis for the logic sequences considered. (The technology for rupture signal detection logic may be evaluated later if the test and analysis results indicate that this method is feasible.)

4.3.1.1 Pressure Sensors

Pressure measurement is a mature industrial technology where the principles are well established and a large number of commercial sensors are available. Passive pressure sensors such as manometers, bourdon tubes, bellows and diaphragm gages convert energy from the fluid system into a mechanical displacement and are the typical HM&E pressure sensor on many existing ships. A description of these instruments is provided in [7,8]. The primary advantage of these mechanical pressure sensors is that no electrical power is needed for their operation. However, experience indicates that the calibration burden is significant, and degradation and malfunction are common. Active pressure sensors typically convert fluid system energy into electrical output, and sensing technologies include variable inductance, piezoresistive, piezoelectric, capacitive and Hall effect, [9,10]. In addition, active sensors which convert fluid system energy to an optical signal and in turn to electrical output are also available commercially. A general discussion of fiber optic sensing technologies is provided in [11] and fiber optic pressure sensing methods for shipboard firemains is described in [12]. The reliability of the sensor technology is evaluated by considering sources of error for pressure instrument installations:

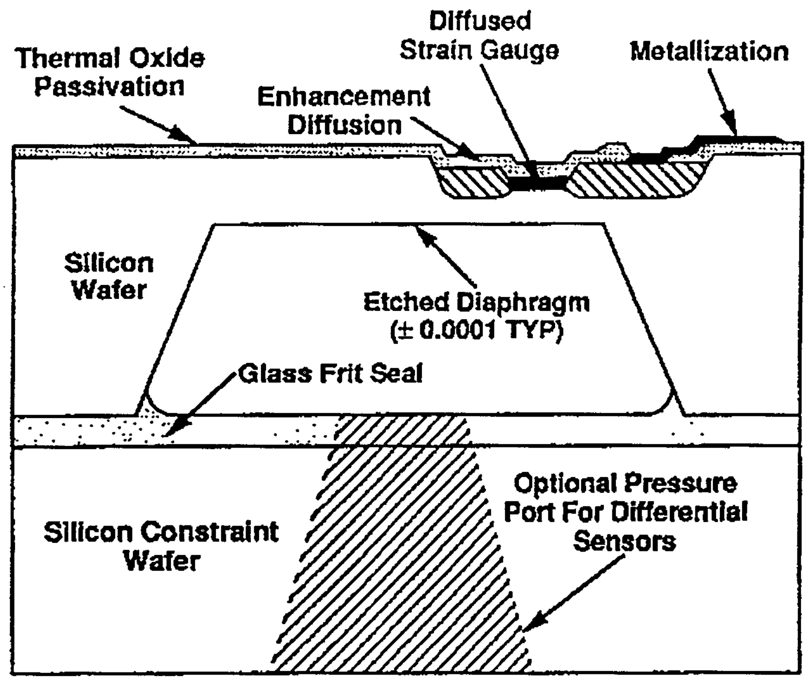
- Calibration. Calibration biases are attributed to non-linearity, hysteresis, and offset of the instrument in addition to the calibration practices used. For pressure transducers, the calibration is often sensitive to ambient temperature so that if measurements are made at temperatures different than the calibration, the bias may significantly increase.

- Installation. Industrial pressure sensors typically are installed using a static pressure tap and a small diameter impulse line connecting the pipe and sensor. Installation biases are attributed to the elevation of the sensor/transducer relative to the pipe, the imperfections in the static tap, and the length of the impulse line. The bias attributed to the elevation differences can be corrected if the temperature of the fluid in the impulse line is known. The bias due to the imperfections of the static tap are minimized by ensuring that the tap hole has a small diameter, is perpendicular, and does not have burrs or rounded corners, [13-15]. The tap bias can be expressed as fraction of the velocity head and is considered negligible for most industrial static pressure measurements but may be significant for small differential measurements. The bias due to the length of the impulse line applies to transient measurements only. The impulse line bias may be substantial for gases but usually can be neglected for liquids based on the analysis methods in [7].
- Data Acquisition. The bias due to data acquisition is attributed to misadjustments in the signal conditioning (e.g., filters, amplifiers, temperature compensation) and analog to digital (A/D) conversion along with mistakes in the computer algorithms which process the digital data. The bias due to these data acquisition effects are negligible for many industrial installations because calibration practices compensate for their effects; however, bias due to data acquisition is not uncommon since calibration practices do not always correct these biases and system modifications may increase their effects.
- Degradation. Degradation biases are errors in the instrument loop which are not corrected with calibration practices. In addition to sensor malfunction, degradation can be caused by collection of non-condensibles in the impulse lines (for liquid systems), collection of condensibles in the impulse lines (for gas systems), debris blockage of the impulse lines, and damage/fouling buildup in the vicinity of the tap.

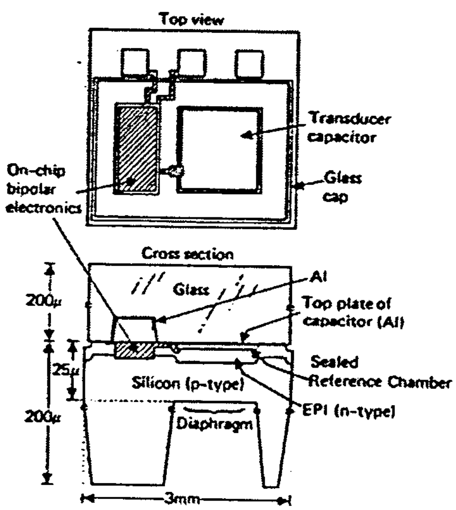
Our review of the commercial pressure sensing technologies indicates that all sensing methods are susceptible to errors described above and that there is no inherent advantage in any of these technologies. Instead, the design of the sensor installation should compensate for these factors to ensure reliable measurements.

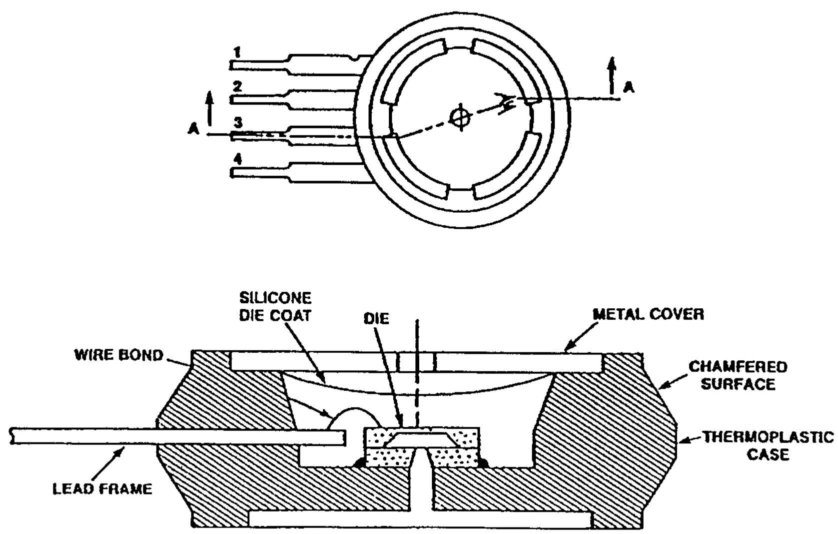
The most significant development in commercial pressure sensor technology is the widespread use of silicon as a sensing element. Since miniature silicon sensors are in wide use, are inexpensive and can be embedded in mechanical components such as valves and piping, use of this technology in reflexive fluid systems is expected. Silicon pressure transducers typically use piezoresistive and capacitive measurement methods. Simplified schematic representations of sensor packages are shown in Figure 8. The capabilities of silicon as a pressure sensor have been established for over 20, years as described in [16,17]; however, use of silicon pressure sensors has become popular only over the past 10 years. This popularization is attributed to the reduction in the cost of fabrication and the development of reliable signal conditioning methods for amplification, linearization, and temperature compensation.

Due to its popularity, the silicon pressure measurement methods establish the standard for reliability to which other technologies should be compared. Since use of silicon pressure sensors is not prevalent in current HM&E instruments, investigation to quantify the reliability (calibration requirements, degradation mechanisms, and maintenance) for both embedded and stand-alone commercial sensors is warranted.



(a) Piezoresistive Wafer-Level Package





(b) Capactive Sensor Package

(c) Plastic Chip Carrier

(Copied from References 9 and 10)

Figure 8. Silicon Pressure Sensors

4.3.1.2 Flow Sensors

Flow measurement is a mature industrial technology where many sensing techniques are well established and a large number of commercial sensors are available. Some of the more common commercial sensing methods include differential pressure, ultrasonic, thermal mass, vortex shedding and electromagnetic. A summary description of these methods along with others is provided in [18]. In general, permanent flow instrumentation is not installed in HM&E systems and therefore Navy reliability experience is limited. Experience in the power and process industries (which are considered to be similar to the HM&E systems) indicates that calibration and maintenance burden can be extensive, particularly for high accuracy measurements. The reliability of the flow sensor technology is evaluated by considering sources of error for pressure instrument installations:

- Calibration. Calibration biases are attributed to non-linearity, hysteresis and offset of the instrument in addition to the calibration practices used. Calibration using a flow loop and a weigh tank (i.e., wet calibration) is used to reduce the uncertainty associated with installation practices and flow profile. In practice, a wet calibration is required for high accuracy to determine a flowmeter constant which accounts for non-ideal effects (even for the most established technologies such as differential pressure).
- Flow Profile. The velocity profile inside a pipe varies with different flow rates, temperatures, fluid properties, upstream/downstream disturbances, and roughness/fouling. For straight smooth pipe with undisturbed upstream conditions, the variation in velocity profile is well established for different flowrates, temperatures and fluid properties based on boundary layer theory [19]. However, typical shipboard conditions are different from these idealized conditions. As a result, all industrial flowmeters are subject to bias due to uncertainties in the velocity profile for the installed conditions. For standard differential pressure elements such as nozzles and orifices, the bias attributed to upstream disturbances such as elbows has been studied, [20]. For other flow measurement technologies, the impact of upstream flow disturbances is not well established in the open literature. For instance, manufacturers of ultrasonic and electromagnetic flowmeters typically require a minimum length of straight upstream piping to ensure accurate measurements, and standards describe this effect as a source of error, [21, 22].
- Installation. Non-ideal installation practice results in a bias in flow measurement. Experience indicates that the small differences between the installation used at a wet calibration and the installation in fluid system can result in significant errors for some designs.
- Data Acquisition. The bias due to data acquisition is attributed to misadjustments in the signal conditioning (e.g., filters, amplifiers, temperature compensation) and A/D conversion along with mistakes in the computer algorithms which process the digital data. The bias due to these data acquisition effects may be negligible for many industrial installations because calibration practices compensate for their effects; however, bias due to data acquisition is not uncommon since calibration

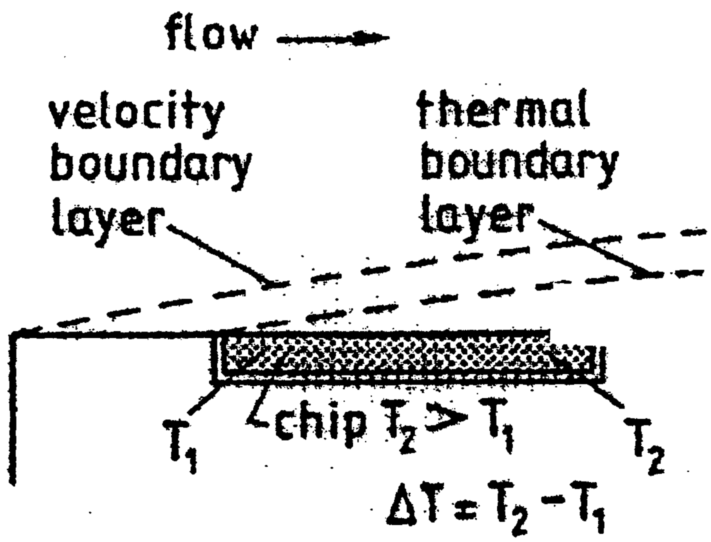
practices do not always correct these biases and system modifications may increase their effects.

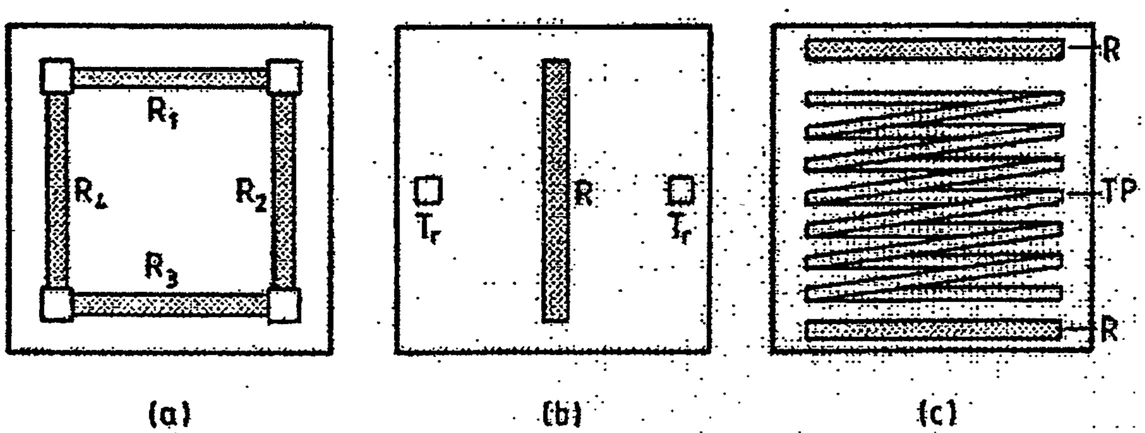
- Degradation. Degradation biases are errors in the instrument loop which are not corrected with periodic calibration practices. For industrial flow measurement, changes in the internal condition of the pipe is the most significant contributor to degradation in the flow measurement which is not corrected with an insitu calibration check. For firemain systems, buildup of biofouling products on the inside surface of the pipe will have a significant impact on the flow measurement.

Differential pressure elements are the most common industrial method of measuring flow. Industry standard methods are available to size flow elements for orifices, venturis, and nozzles, [23,24]. Non-ideal effects such as due to upstream flow disturbances [20], variations in pipe roughness [25], and non-square pressure taps [13,14], have been studied. As a result, differential pressure flow measurements are considered to be the industrial standard to which other methods are compared.

Investigations of the use of differential pressure measurements across firemain valves to measure flow rate have been initiated, [26-28]. These initial results indicate that embedding flow measurement capability in valves is viable based on current commercial pressure sensor and valve technology. Limitations of this method are primarily attributed to compensation required for accurate measurement of low differential pressures. This compensation involves careful initial and followup calibration of the sensor and correction for non-ideal effects. In particular, the non-ideal tap effect is significant with small differential pressures observed with "full-ported" valves. Due to this effect, the measured pressure drop may be different based on flow direction and small changes in the fouling buildup near the taps could significantly change the measured pressure difference. The tap effect can be reduced using a reduced ported valve design but the pressure loss due to the valve increases for this arrangement.

Thermal mass flow measurement methods may be considered for reflexive fluid system implementation since miniaturization of the sensor is possible [29,30]. The operation of the sensor is based on the principle that the heat transfer coefficient is a function of Reynolds number. The temperature difference between a heated temperature sensor in the flow path and an unheated sensor is proportional to flow rate (see Figure 9). Matched thermistors or RTDs are typically used for industrial anemometers which measure gas flow rates. Flow switches for liquid systems based on the thermal mass flow principle are available commercially. However, miniature thermal mass flowmeters and/or thermal mass flowmeters for liquid systems have not been identified commercially. Additional investigation of this method is warranted.





(a) Wheatstone type, (b) two-transistor type, (c) thermopile-based sensor

(*Copied from Reference 17*)

Figure 9. Silicon Thermal Mass Flowmeter

Other flow measurement techniques may be suitable for reflexive fluid system implementation. In particular, established industrial flow measurement techniques such as ultrasonic, vortex shedding and electromagnetic should be investigated further to determine calibration and maintenance requirements to meet reliability needs for a reflexive fluid system. In addition, differential flow technology should be investigated for leak detection. A simple differential flow sensor could be demonstrated by combining two flow sensors with appropriate differential signal conditioning and communication. A differential flow sensor may increase the sensitivity of leak detection (less than 1 gpm), reduce the uncertainty (since a differential measurement is made rather than calculating the difference between two measurements) and reduce the calibration effort by a factor of two.

4.3.2 Communication

To implement a reflexive fluid system design, some communication may be needed to:

- transmit status data to and receive override commands from the supervisory control system,
- exchange status data and fluid system parameter data between neighboring fluid system components (sensors, valves, pumps and tanks), and
- exchange data describing compartment environmental conditions.

The method of communication and interface requirements with the supervisory control system has not been defined, but current technology that permits network communication (transceivers and microprocessors with network protocol) is considered suitable for interface with the supervisory control system. Communication requirements between fluid system components depend on the logic sequence employed. For low pressure logic, the system fluid is the communication medium and a simple hydraulic actuator is needed based on current technology. For hydraulic resistance logic, calculations with pressure and flow data are performed and some communication between sensors and valves may be needed. For flow inventory logic, communication between neighboring valves and flow sensors is required. For rupture detection logic, communication between fluid system sensors, environmental sensors, a microprocessor and between neighboring valves is needed.

In general, the requirements for reflexive fluid component communication involve small amounts of data (pressure, flow and status) transmitted at fairly slow rates (similar to valve closing transients which are several seconds in duration). A number of different communication options can meet these general requirements and methods have not been standardized. Currently, IEEE P1451 is under development to standardize the interface between a smart sensor and a network [31]. The overall objective of IEEE P1451 is to develop an interface standard that isolates the sensor/transducer selection from the network selection. If this objective is met, sensors and control microprocessors could be replaced with different equipment without losing any functional capability. A schematic representation of the IEEE 1451 transducer interface is shown in Figure 10. It is not clear if this IEEE standard will be used. Currently, the commercial market for control networks is fragmented such that no single method has a clear advantage over competing technologies. Some examples of a device-level network which could be used for fluid system reflexive control are:

- DeviceNet—Rockwell Automation, Allen-Bradley
- SDS, Smart Distributed System--Honeywell
- LonWorks—Echelon Corporation
- Profibus-PA
- Modbus Plus

Development of these networks requires integration of compatible hardware and software based on the same communication protocol. Interconnection between these networks is difficult since each has its own technique for addressing, error checking and data format. Suppliers of hardware and software are often limited for each technology which may limit the capability to expand or modify the network. As a result, enlarging or modifying a control network may not be practical if original software or hardware is unsupported.

Due to the status and competition of the commercial technology for control networks, there is a risk that a reflexive fluid system is demonstrated with a technology that is not supported in a couple of years. As a result, development of reflexive system design must be "open" with respect to the communication technology used. In addition, use of uncomplicated logic and communications should be pursued so that fluid system maintenance is facilitated when installed communication technology becomes obsolete.

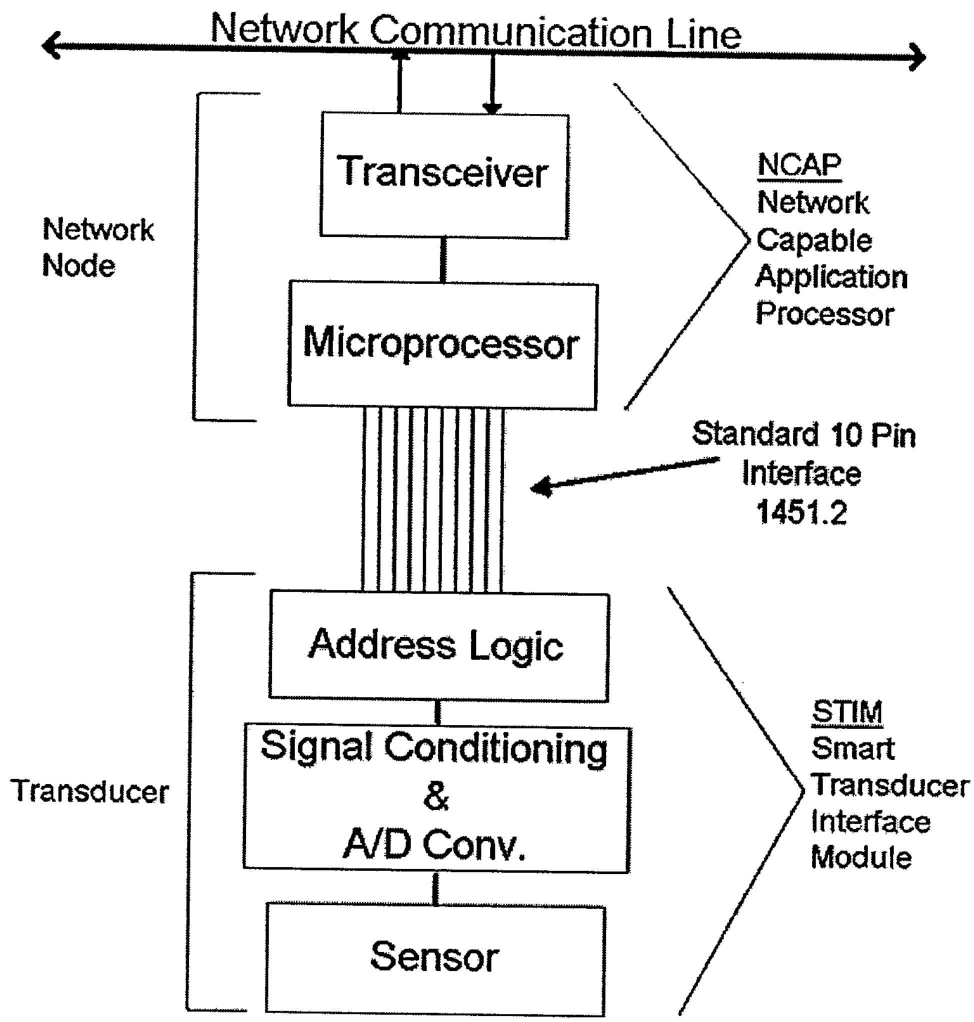


Figure 10. IEEE 1451 Smart Sensor Configuration

4.3.3 Valves and Actuators

A variety of industrial valve and actuator designs would meet the requirements of a reflexive fluid system. This section provides a brief introduction to the designs which may be considered for shipboard reflexive fluid system development. A more complete description of various designs is provided in [32].

4.3.3.1 Gate Valves (Figure 11)

Gate valves operate with a sliding stem where a plate or disk is moved across the flow path. There are different types of plates, seats and stems. They are often used in high pressure and temperature applications. The plates can experience large vibration during transients and are not usually used to throttle. They provide a strong seal but are prone to seat and disk wear which can be caused by the friction encountered during seating and unseating. Additional force is required to seat or unseat the valve compared to the hydraulic force generated during transient. The seating area is prone to contamination buildup if the valve is normally in the open position. Gate valves tend to be slower than most other types and require much higher actuation forces.

4.3.3.2 Globe Valves (Figure 12)

A globe valve is a sliding stem valve characterized by an offset flow path. The plug acts in line with the flow. The valve provides a strong seal and the flow pressing the plug along its axis of motion gives additional sealing force. When the valve is open the plug retracts into its large "globe" cavity. The globe design gives strong sealing without much interruption of flow from the plug in the open position. The curvature of the cavity results in more streamlined flow.

4.3.3.3 Ball Valves (Figure 13)

Ball or ball segment valves are the most common types of rotary valves. In the case of the full ball valve, the ball has a cylindrical hole through the centerline. When the cylindrical hole is aligned in the direction of the flow, fluid will pass, and the valve is open. When the actuator rotates the ball 90°, the cylindrical hole in the ball is perpendicular to the flow and the valve is sealed. Ball valves are more responsive and quicker than conventional stem valves. Common ball valve materials are metal, plastic, or metal-coated plastic. The size of the ball affects the bearing torque and the bearing life. A larger ball will require more torque to turn, but the life of the bearing will increase. A small ball will be easier to turn but the bearing life will be reduced.

4.3.3.4 Butterfly Valves (Figure 14)

A typical butterfly valve consists of a circular disk connected to an actuating rod through the diameter. The actuating rod is perpendicular to the direction of flow. When the disk face is parallel to the direction of flow, the valve is open. When the actuating rod is rotated 90°, the disk face is perpendicular to the direction of flow, the circumference of the disk is fitted against the circumference of the valve housing, and the valve is closed. A sealing gasket is usually fitted around the circumference of the disk to help completely seal upon closing. The principal advantage of a butterfly valve is the low weight and size. The principal disadvantage is valve leakage when the sealing gasket is damaged or worn. In addition, a large torque must be applied to seat and unseat the valve. A high-performance butterfly valve (HPBV) has been developed to address these deficiencies. The concept of the HPBV is the same except the disk is offset from the actuating rod by a small difference. This creates a cam effect upon seating. The disk is not pressed into place but is slid into the seat. The benefits are slower seal wear, reduced seating and unseating force, reduced static torque and operation with greater pressure differentials.

4.3.3.5 Motor Operators

Motor operators consist of an electric motor coupled to a gear assembly which drives the valve. This type of actuation is capable of producing linear or rotational actuation. Where rotational motion is needed, the motor's gear assembly can be connected directly to the valve. Where linear translation is needed a rack and pinion system can be used, where precision and control are required a ball screw drive can be substituted. These systems are capable of producing high torque and stem thrust. Motor operators are slow compared to other types of actuation (hydraulic and pneumatic). They have limited throttling capability because stabilizing mechanisms in mid stroke are typically not provided.

4.3.3.6 Solenoid Operators

Solenoid operators generate an electromagnetic field around a metallic plunger that drives the valve. The strength of the field determines the position of the plunger that is measured by a LVDT (Linear Variable Differential Transformer). This method of actuation is advantageous compared to motor operators because a mechanical gear assembly is not needed. An electrical signal can be sent from a controller to directly operate the valve. These actuators exhibit reliable open/closed characteristics as well as throttling characteristics. They do have limited thrust and can be more costly than pneumatic operators.

4.3.3.7 Hydraulic Operators

Hydraulic operators use a piston-cylinder assembly or a spring-diaphragm assembly to drive the valve stem. An incompressible fluid provides the source of energy to move the valve. Hydraulic systems are capable of quick stroke times. The addition of volume booster can increase the stroke while the addition of positioners can increase the control and overall performance. These actuators are often used for automated throttling control applications and demonstrate linear response.

The electrohydraulic actuator is a combination of the motor operator and hydraulic actuator. These actuators have a hydraulic fluid filled piston-cylinder assembly with the addition of an on-board motor and fluid reservoir. The benefits are similar to the hydraulic operators with respect to linearity, stability and stroke time.

4.3.3.8 Air Operators

Pneumatic operators are the most popular of all the actuators. All types of pneumatic valves are susceptible to non-linearity because the working fluid is compressible. There are three main classifications of pneumatic valves: spring-diaphragm, piston-cylinder and rotary. Pneumatic valves typically operate with control air at pressures less than 100 psig. The principal advantages of pneumatic actuators are their quick response and their capability to operate without electrical power. Their principle disadvantage is the potential for malfunction due to moisture and contamination in the air supply.

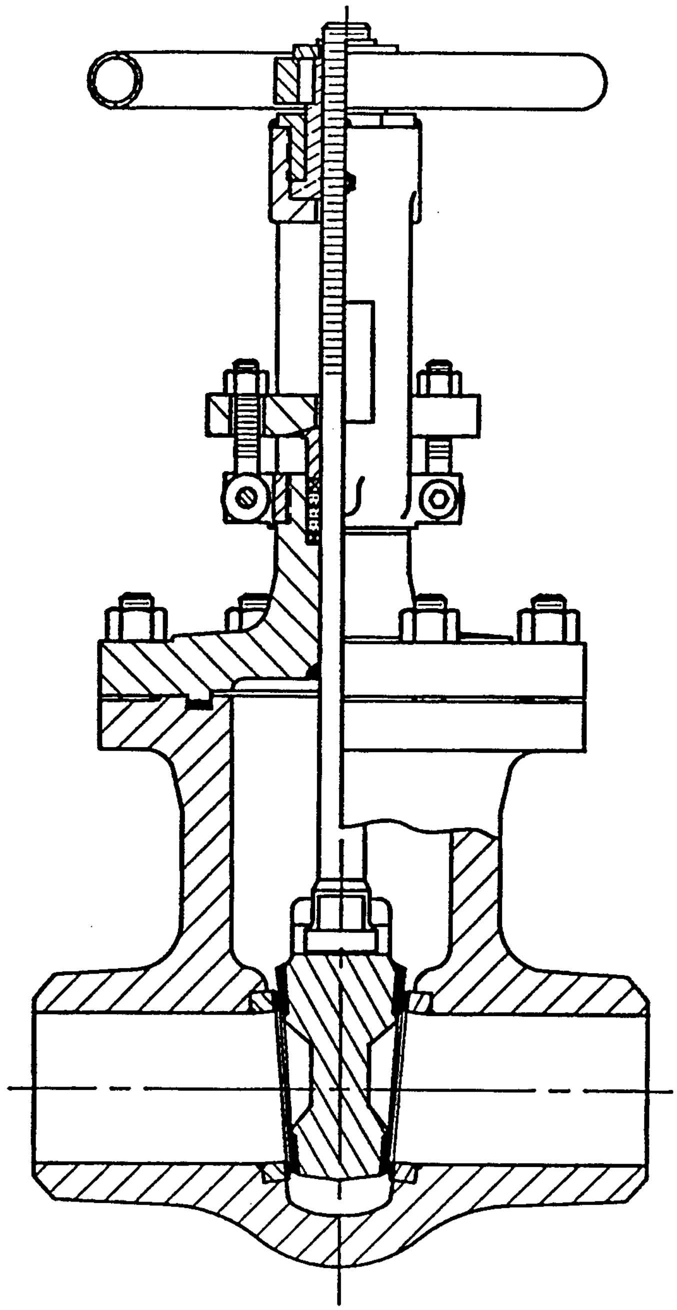


Figure 11. Simplified Cross-Section of a Gate Valve

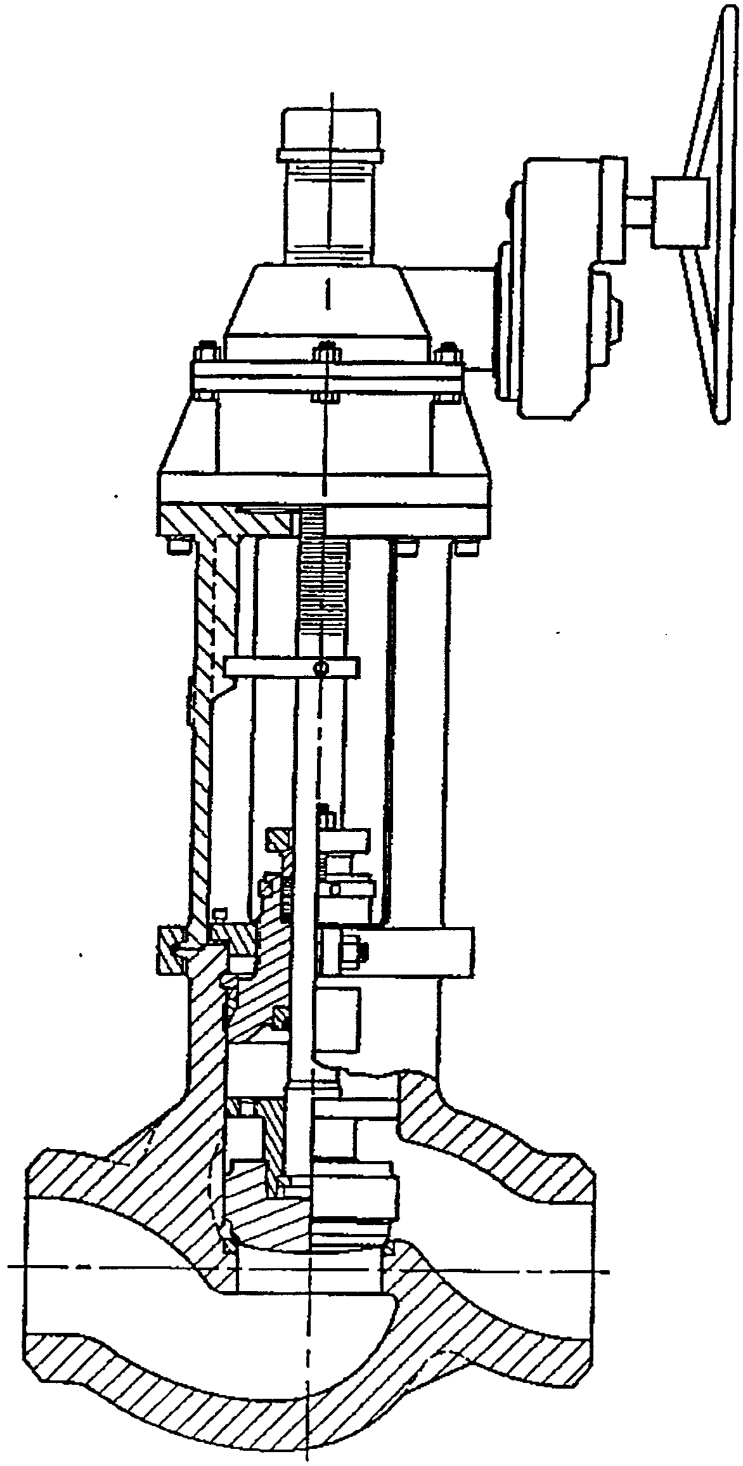


Figure 12. Simplified Cross-Section Globe Valve

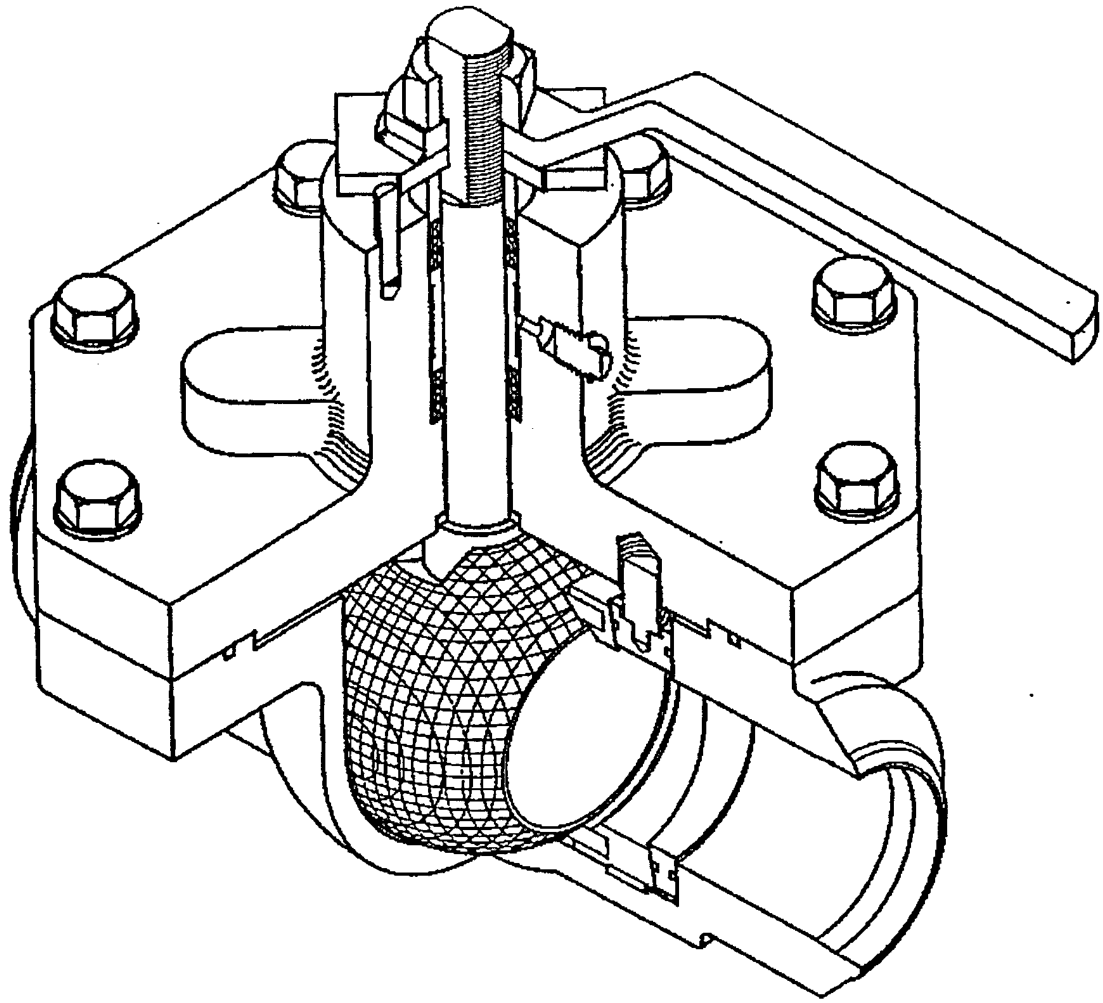


Figure 13. Simplified Cross-Section of a Ball Valve

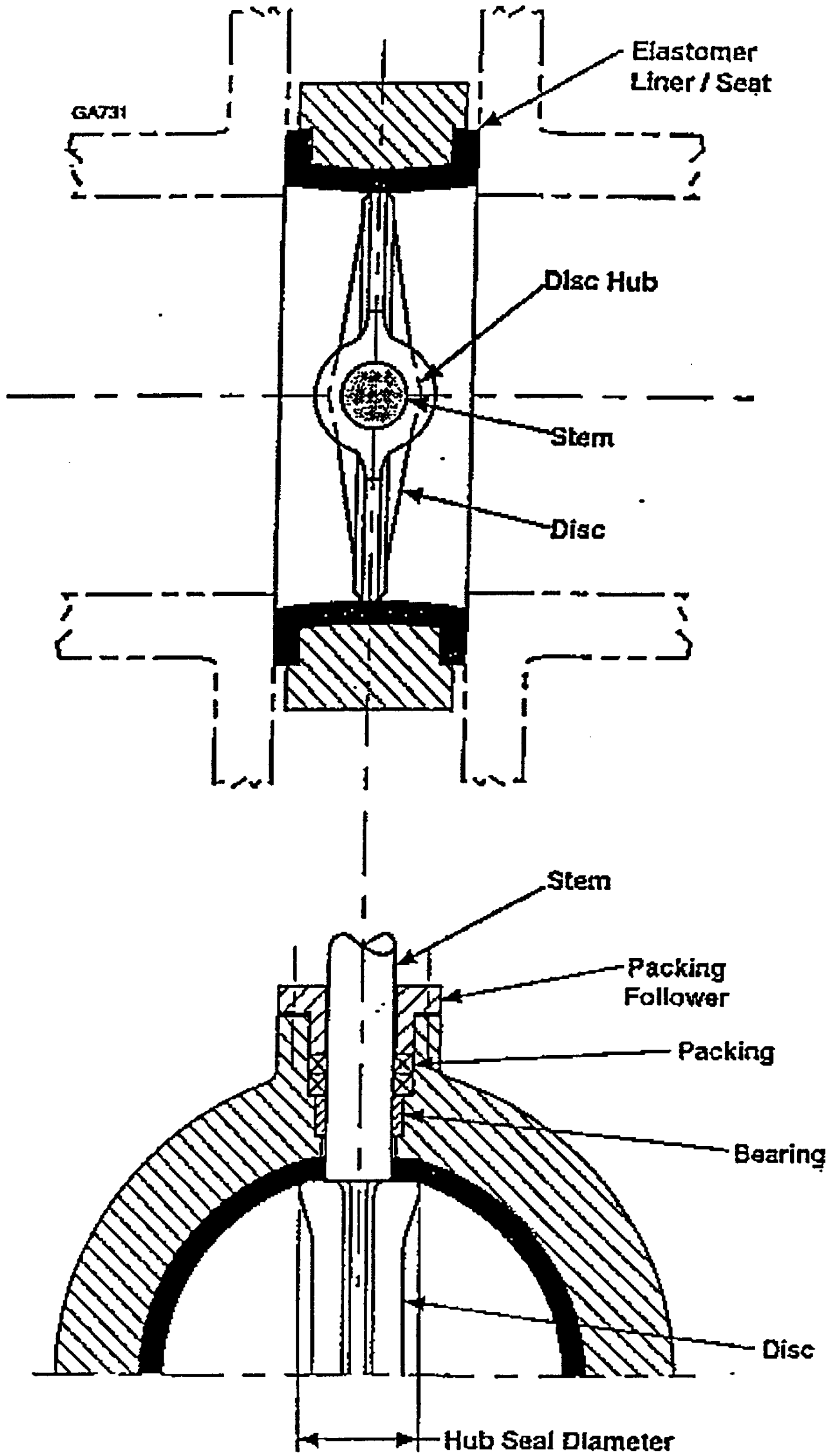


Figure 14. Simplified Cross-Section of a Butterfly Valve

5.0 Trade-Off Analysis and Conclusions

The conclusions for this evaluation and plans for continued development of a reflexive fluid system involve a trade-off between simplicity and survivability. A simple fluid system has few active components (pumps and valves), is easy to operate and inexpensive to maintain. A survivable system has redundant components and responds automatically to damage conditions. The key trade-off issues and conclusions for this evaluation are as follows:

Pumps Versus Smart Valves. The evaluation of firemain architectures indicates that the number of flow loops is directly related to the number of pumps required and inversely related to the number of smart valves. As the number of pumps or smart valves increases, the installation and subsequent life cycle cost for the system increases. However, the cost of a pump is expected to be substantially greater than a smart valve. Each shipboard fire pump requires the installation of a sea chest, suction piping, motor and foundation, discharge riser, associated valves and electrical components. Furthermore, Navy experience indicates that fire pumps and motors are a maintenance burden. Consequently, a design with fewer pumps is preferred. Development of a smart valve is a key portion of a reflexive fluid system development.

Isolation Versus Communication. The evaluation of segregation sequences indicates that communication between sensors, valves and pumps improves the capability to optimally restore system operation following damage. In particular, smaller ruptures may be undetected and intact sections of piping may be isolated without flow if communication between neighboring components is not established. The use of communication may adversely impact survivability since new failure modes are introduced (such as loss of the network and malfunction of a neighboring component). Implementation of reliable device communication methods is a key aspect of investigation for reflexive fluid system development.

Simple Versus Comprehensive Logic. The technology study and evaluation of segregation sequences indicate that development of comprehensive leak detection methods will be difficult. For example, low pressure logic is simple to implement by installing a commercial hydraulic spring loaded valve (so that hydraulic pressure opens the valve and the spring closes the valve on loss of pressure). To overcome the limitations of this installation, additional logic will have to be developed. This is attributed to (1) the limitations in reliability and accuracy of commercial industrial pressure and flow sensors, (2) the complexity of pressure and flow combinations for typical shipboard fluid systems and (3) the risks associated with the development of emerging sensor technologies. Based on this conclusion, evaluation of the performance and reliability of simple rupture detection methods compared with comprehensive logic will be investigated.

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Appendix A

Flow Requirements and Number of Pumps

This appendix contains the following three tables:

Table A-1. Hydraulic Analysis Flow Requirements for Offset Loop and Dual Main Architectures

Table A-2. Hydraulic Analysis Flow Requirements for Zonal Architecture

Table A-3. Number of Pumps Necessary to Meet Flow Requirements

The following acronyms have been used:

AFFF	Aqueous Film Forming Foam
CBR	Chemical, Biological or Radiological attack
CIWS	Close-in Weapon System
SSGTG	Ship Service Gas Turbine Generators
WDCM	Washdown Countermeasure

Table A-1. Hydraulic Analysis Flow Requirements for Offset Loop and Dual Main Architectures

Group[1]	Description of Load	Load (gpm)	Baseline Cases - No Pipe Damage[2]				Pipe Damage Cases[2]	
			Normal Operation (Case 1)	Missile Hit w/ CBR (Case 2)	Mine Hit (Case 3)	Main Machinery Space Fire (Case 4)	Missile Hit (Case 5)	Mine Hit (Case 6)
1	WDCM	360		X			X	
	Magazine Sprinkling (backup for group 2)	1590						X
	AFFF Station 1	1000						
	Misc. Sprinkling	660						
	Fire Plugs	90 per plug		X (2)	X (2)		X(2)	X(2)
	CIWS Cooling	25		X	X		X	X
	Total		0	565	205	0	565	1795
2	Drainage Eductors	590			X			
	Magazine Sprinkling	1590		X	X		X	
	Misc. Sprinkling	660			X			
	Fire Plugs	90 per plug						
	Towed Sonar Cooling	1	X	X	X	X	X	
	Total		1	1591	2841	1	1591	0
3	WDCM	1530		X				
	Misc. Sprinkling	660		X				
	Fire Plug	90 per plug		X(2)				
	Total		0	2370	0	0	0	0

Group[1]	Description of Load	Load (gpm)	Baseline Cases - No Pipe Damage[2]				Pipe Damage Cases[2]	
			Normal Operation (Case 1)	Missile Hit w/ CBR (Case 2)	Mine Hit (Case 3)	Main Machinery Space Fire (Case 4)	Missile Hit (Case 5)	Mine Hit (Case 6)
4	Drainage Eductors	590						
	Emergency Cooling (SSGTG)	180						
	Misc. Sprinkling	660						
	Fire Plug	90 per plug		X(2)	X(2)	X(2)	X(2)	X(2)
	Total		0	180	180	180	180	180
5	WDCM	1275		X			X	
	Misc. Sprinkling	660						
	Fire Plug	90 per plug		X(2)		X(2)	X(2)	
	Total		0	1455	0	180	1455	0
6	Drainage Eductors	590						
	Emergency Cooling (SSGTG)	180						
	Misc. Sprinkling	660				X		
	Fire Plug	90 per plug						
	Total		0	0	0	660	0	0
7	WDCM	300		X			X	
	Magazine Sprinkling (backup for group 8)	1590						
	AFFF Station 2	1000				X		
	Misc. Sprinkling	660						
	Fire Plug	90 per plug						
	CIWS Cooling	25		X	X		X	X
	Total		0	325	25	1000	325	25

Group[1]	Description of Load	Load (gpm)	Baseline Cases - No Pipe Damage[2]				Pipe Damage Cases[2]	
			Normal Operation (Case 1)	Missile Hit w/ CBR (Case 2)	Mine Hit (Case 3)	Main Machinery Space Fire (Case 4)	Missile Hit (Case 5)	Mine Hit (Case 6)
8	Drainage Eductors	590						
	Magazine Sprinkling	1590						
	Misc. Sprinkling	660						
	Fire Plug	90 per plug				X(2)		
	Steering Gear and Shaft Seals Cooling	12	X	X	X	X	X	X
	Total		12	12	12	192	12	12
TOTAL			13	6498	3263	2213	4128	2012

NOTES:

1. Firemain service loads have been divided into eight groups with two groups in each fire zone. The numbering is forward to aft with groups 1, 3, 5 and 7 are supplied by the "high" main and groups 2, 4, 6, and 8 are supplied by the "low" main.
2. The cases are described as follows:

<u>Case 1:</u> Normal Operation. No Pipe Damage. Only loads required for peacetime cruising are accounted for.

<u>Case 2:</u> Missile Hit with a CBR. Missile hit is located in Fire Zone 2 at a high elevation (near Branch Group 3 on the port main). A CBR is assumed to occur with the missile hit. The firemain remains intact.

<u>Case 3:</u> Mine Hit forward and low, near Branch Group 2 within fire zone 1. The fireman remains intact.

<u>Case 4:</u> Main Machinery Space Fire located low, mid to aft of the ship, near Branch Group 6. The firemain remains intact.

<u>Case 5:</u> Missile Hit with a CBR. Missile hit is located in Fire Zone 2 at a high elevation (near Branch Group 3 on the port main). A CBR is assumed to occur with the missile hit. Branch Group 3 and components located near it are damaged by the hit. A double ended rupture 60' long.

<u>Case 6:</u> Mine Hit forward and low, near Branch Group 2 within fire zone 1. Branch group 2 and components near it are damaged by the hit. A double ended rupture 60' long.

Table A-2. Hydraulic Analysis Flow Requirements for Zonal Architecture

Group[1]	Description of Load	Load (gpm)	Baseline Cases - No Pipe Damage[2]				Pipe Damage Cases[2]	
			Normal Operation (Case 1)	Missile Hit w/ CBR (Case 2)	Mine Hit Case 3)	Main Machinery Space Fire (Case 4)	Missile Hit (Case 5)	Mine Hit (Case 6)
1	WDCM	360		X			X	
	AFFF Station 1	1000						
	Misc. Sprinkling	660						
	Fire Plugs	90 per plug		X (2)	X (2)		X(2)	
	CIWS Cooling	25		X	X		X	
	Total		0	565	205	0	565	0
2	Drainage Eductors	590			X			
	Magazine Sprinkling	1590		X	X		X	
	Misc. Sprinkling	660			X			
	Fire Plugs	90 per plug						
	Towed Sonar Cooling	1	X	X	X	X	X	
	Total		1	1591	2841	1	1591	0
3	WDCM	1530		X				
	Misc. Sprinkling	660		X				
	Fire Plug	90 per plug		X(2)				
	Total		0	2370	0	0	0	0

Group[1]	Description of Load	Load (gpm)	Baseline Cases - No Pipe Damage[2]				Pipe Damage Cases[2]	
			Normal Operation (Case 1)	Missile Hit w/ CBR (Case 2)	Mine Hit Case 3)	Main Machinery Space Fire (Case 4)	Missile Hit (Case 5)	Mine Hit (Case 6)
4	Drainage Eductors	590						
	Magazine Sprinkling (backup for Group 2)	1590						X
	Emergency Cooling (SSGTG)	180						
	Misc. Sprinkling	660						
	Fire Plug	90 per plug		X(2)	X(2)	X(2)		X(2)
	Total Load		0	180	180	180	0	1770
5	WDCM	1275		X			X	
	Misc. Sprinkling	660						
	Fire Plug	90 per plug		X(2)		X(2)	X(2)	
	Total		0	1455	0	180	1455	0
6	Drainage Eductors	590						
	Magazine Sprinkling (backup for group 8)	1590						
	Emergency Cooling (SSGTG)	180						
	Misc. Sprinkling	660				X		
	Fire Plug	90 per plug						
	Total		0	0	0	660	0	0

Group[1]	Description of Load	Load (gpm)	Baseline Cases - No Pipe Damage[2]				Pipe Damage Cases[2]	
			Normal Operation (Case 1)	Missile Hit w/ CBR (Case 2)	Mine Hit Case 3)	Main Machinery Space Fire (Case 4)	Missile Hit (Case 5)	Mine Hit (Case 6)
7	WDCM	300		X			X	
	AFFF Station 2	1000				X		
	Misc. Sprinkling	660						
	Fire Plug	90 per plug						
	CIWS Cooling	25		X	X		X	X
	Total		0	325	25	1000	325	25
8	Drainage Eductors	590						
	Magazine Sprinkling	1590						
	Misc. Sprinkling	660						
	Fire Plug	90 per plug				X(2)		
	Steering Gear and Shaft Seals Cooling	12	X	X	X	X	X	X
	Total		12	12	12	192	12	12
TOTAL			13	6498	3263	2213	4128	2012

NOTES:

1. Firemain service loads have been divided into eight groups with two groups in each fire zone. The numbering is forward to aft with groups 1, 3, 5 and 7 are supplied by the "high" main and groups 2, 4, 6, and 8 are supplied by the "low" main.
2. The cases are described as follows:

   <u>Case 1:</u> Normal Operation. No Pipe Damage. Only loads required for peacetime cruising are accounted for.

   <u>Case 2:</u> Missile Hit with a CBR. Missile hit is located in Fire Zone 2 at a high elevation (near Branch Group 3 on the port main). A CBR is assumed to occur with the missile hit. The firemain remains intact.

   <u>Case 3:</u> Mine Hit forward and low, near Branch Group 2 within fire zone 1. The fireman remains intact.

   <u>Case 4:</u> Main Machinery Space Fire located low, mid to aft of the ship, near Branch Group 6. The firemain remains intact.

Case 5: Missile Hit with a CBR. Missile hit is located in Fire Zone 2 at a high elevation (near Branch Group 3 on the port main). A CBR is assumed to occur with the missile hit. Branch Group 3 and components located near it are damaged by the hit. A double ended rupture 60' long.

Case 6: Mine Hit forward and low, near Branch Group 2 within fire zone 1. Branch group 2 and components near it are damaged by the hit. A double ended rupture 60' long.

Table A-3 Number of Pumps Necessary to Meet Flow Requirements

Damage Scenario (Note 1)	Architecture (Notes 2 and 3)		
	Offset Loop	Dual Main	Zonal
Case 2 - Missile Hit w/ CBR, no pipe damage	5 R +1 O = 6 total	*Port:* 4 R + 1 O = 5 total *Starboard:* 2 R + 1 O = 3 total	Zone 1: 2 R + 1 O = 3 total Zone 2: 2 R + 1 O = 3 total Zone 3: 1 R + 1 O = 2 total Zone 4: 1 R + 1 O = 2 total
Case 3 - Mine Hit, no pipe damage	3 R + 1 O = 4 total	*Port:* 1 R + 1 O = 2 total *Starboard:* 3 R + 1 O = 4 total	Zone 1: 2 R + 1 O = 3 total Zone 2: 1 R + 1 O = 2 total Zone 3: 0 R + 1 O = 1 total Zone 4: 1 R + 1 O = 2 total
Case 4 - Machinery Space Fire	2 R + 1 O = 3 total	*Port:* 1 R + 1 O = 2 total *Starboard:* 1 R + 1 O = 2 total	Zone 1: 1 R + 1 O = 2 total Zone 2: 1 R + 1 O = 2 total Zone 3: 1 R + 1 O = 2 total Zone 4: 1 R + 1 O = 2 total
Case 5 - Missile Hit with CBR, pipe break at branch group 3	3 R + 1O + 1 D = 5 total	*Port:* 2 R + 1O + 1 D = 4 total *Starboard:* 2 R + 1O = 3 total	Zone 1: 2 R + 1O = 3 total Zone 2: lost to damage Zone 3: 1R + 1O = 2 total Zone 4: 1 R + 1O = 2 total
Case 6 - Mine Hit, pipe break at branch group 2	2 R + 1 O + 1 D = 4 total	*Port:* 2 R + 1O = 3 total *Starboard:* 1 R + 1O + 1 D = 3 total	Zone 1: lost to damage Zone 2: 2 R + 1O = 3 total Zone 3: 0 R + 1O = 1 total Zone 4: 1 R + 1O = 1 total
Worst Case - Greatest number of pumps necessary	6	*Port: 5* *Starboard: 4* 9 total	Zone 1: 3 Zone 2: 3 Zone 3: 2 (3 if damage occurs aft of ship) Zone 4: 2 (3 if damage occurs aft of ship) 12 pumps total

Notes:

1. All damage scenarios assume one pump is out of service. This would be in addition to pumps lost due to pipe damage in cases 5 and 6.
2. Number of pumps required is calculated based on a maximum allowable pump flow rate of 1500 gpm (110 psid) for a 1650 gpm runout rated pump.
3. "O" indicates a pump out of service. "D" indicates a pump lost due to damage. "R" indicates a pump required to meet flow requirements.

Appendix B

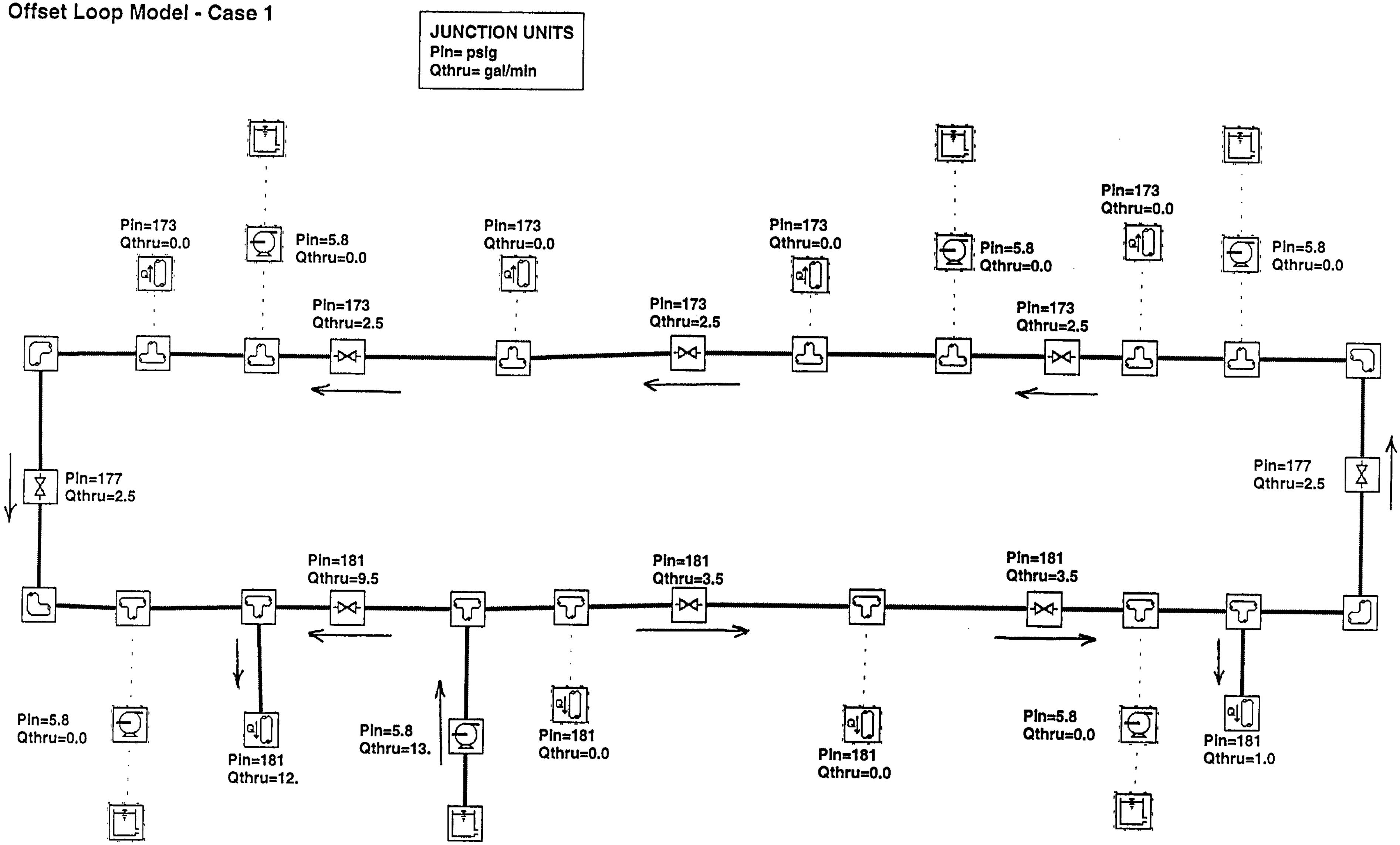
Hydraulic Analysis Results

This appendix contains the graphical output of the AFT Fathom flow analyses. Junction data is displayed for pumps, smart valves, and branch groups.

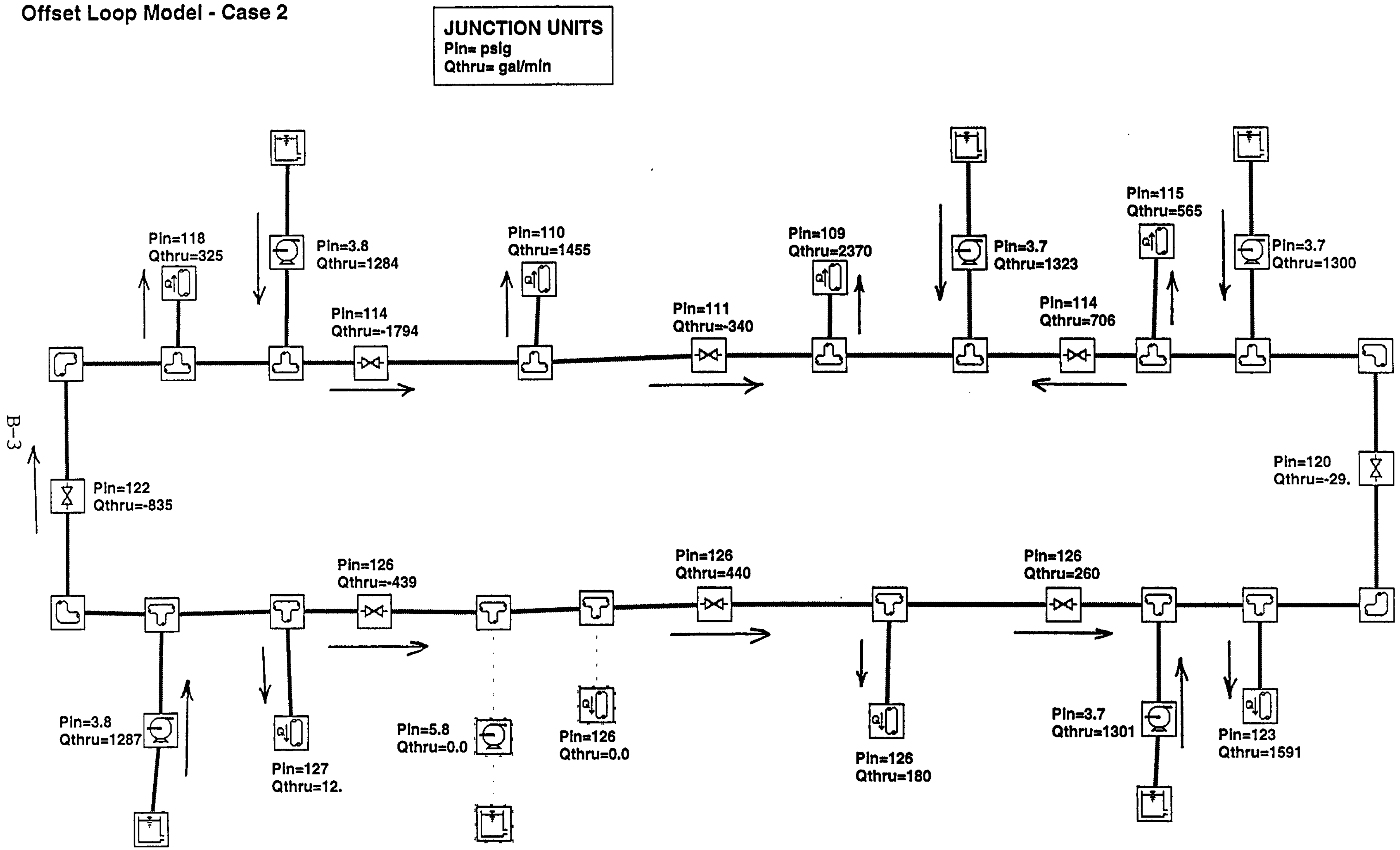
Pin junction inlet pressure (psig)
Qthru flow rate from inlet to outlet of a junction (gpm)

For pumps, the junction inlet is the pump suction and the outlet is the pump discharge. For branch groups, the junction inlet is the pipe connection to the firemain. For smart valves, no inlet convention was used. The output has been marked-up to show flow directions.

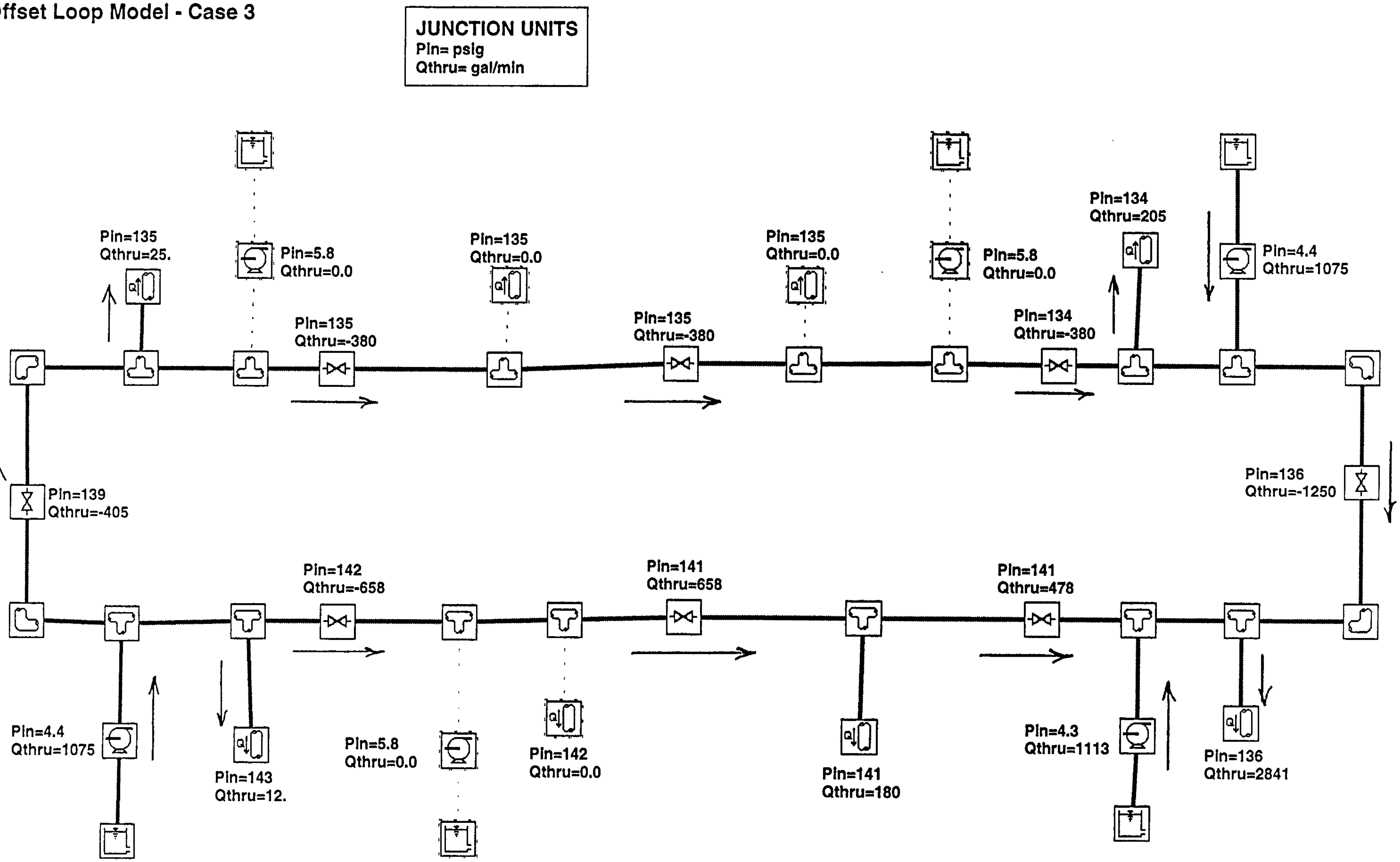
Offset Loop Model - Case 1



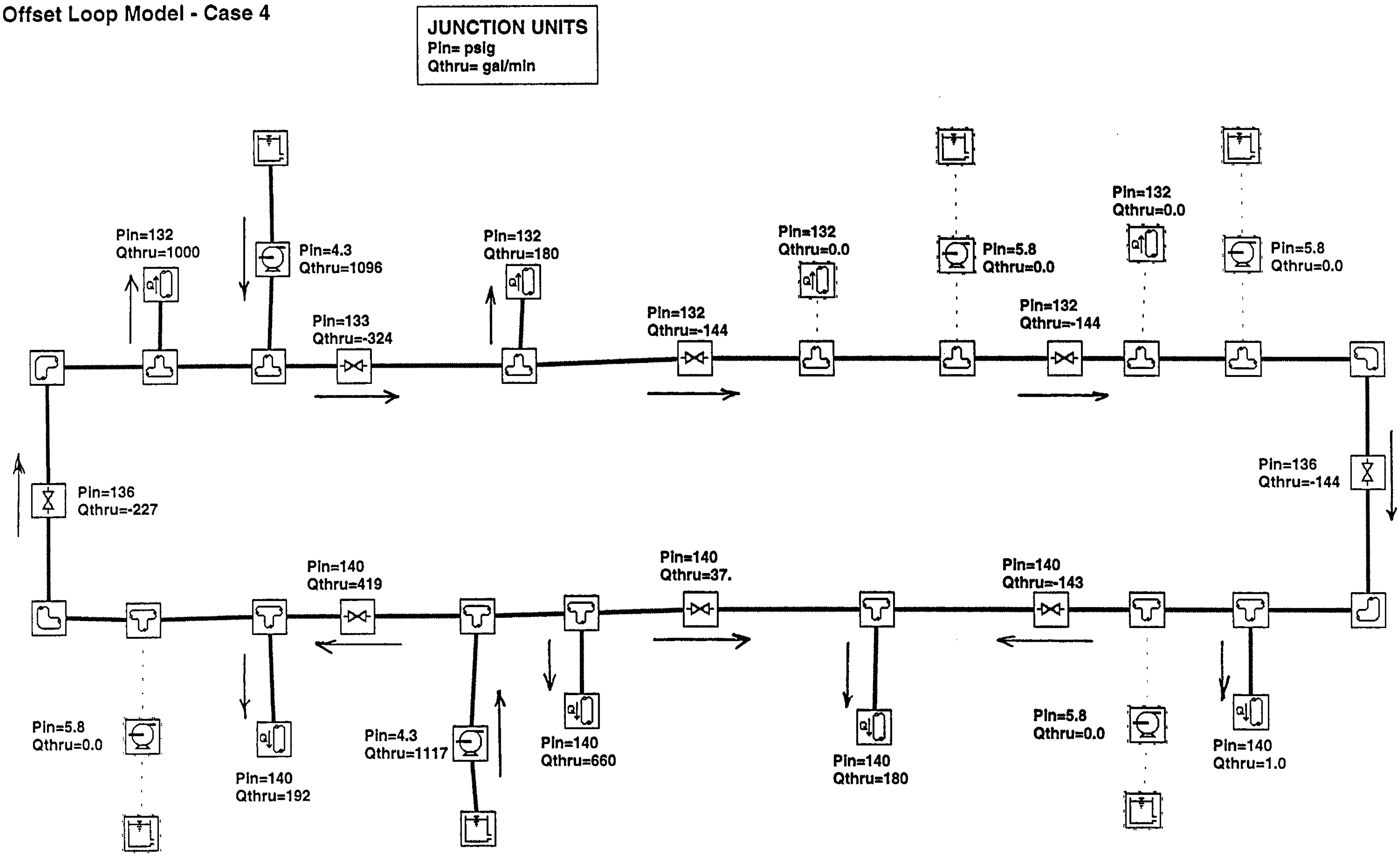
Offset Loop Model - Case 2



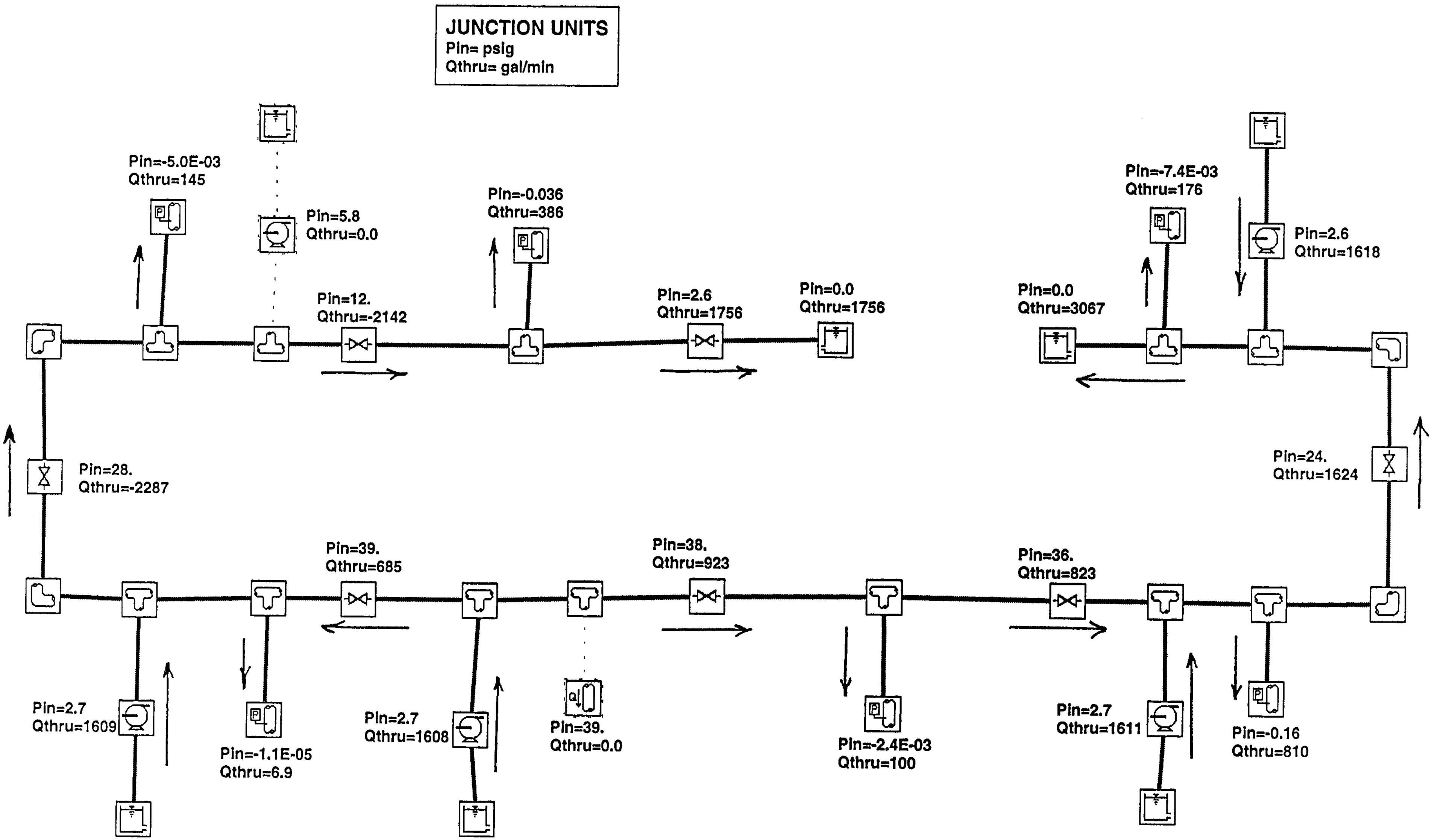
Offset Loop Model - Case 3



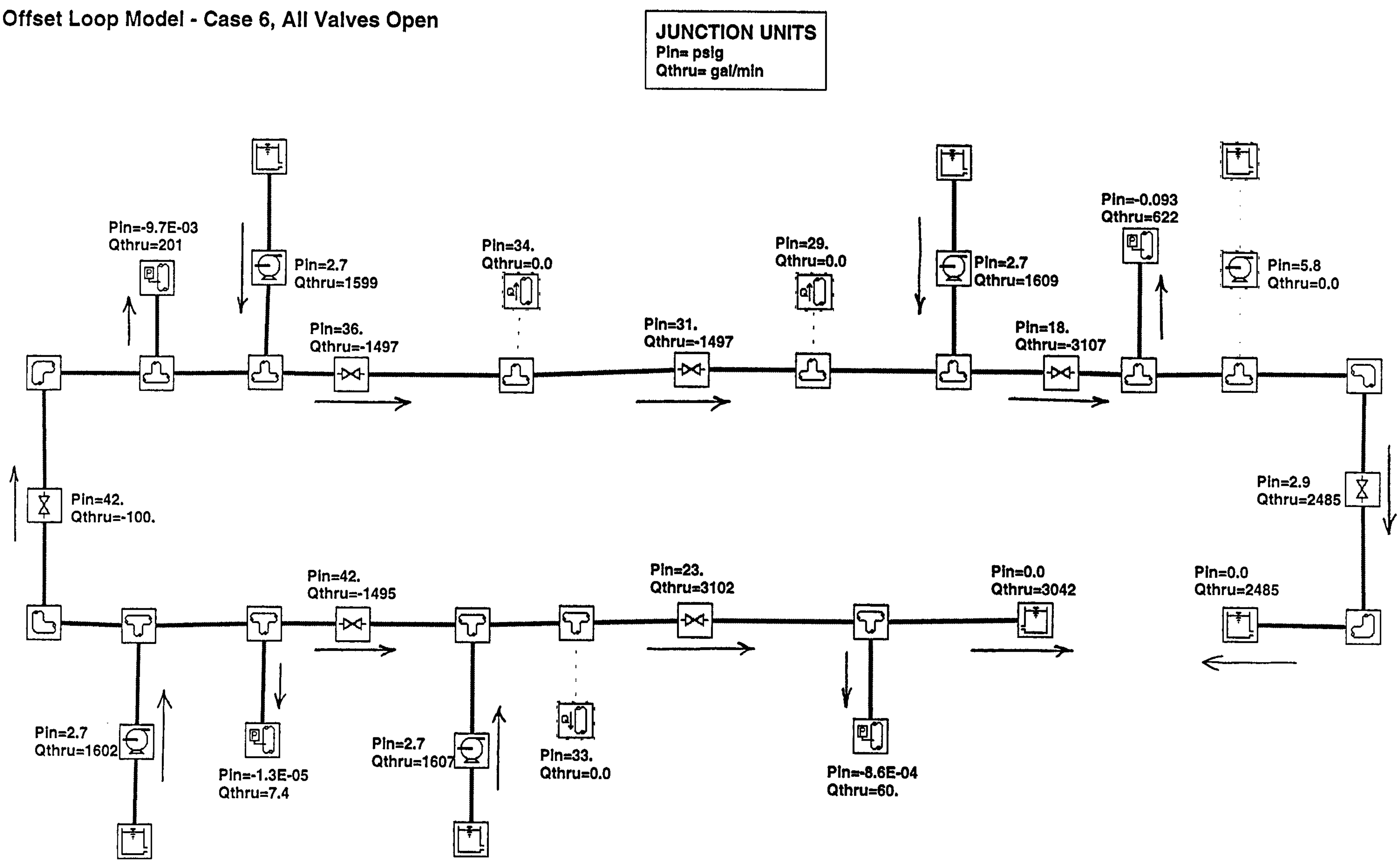
Offset Loop Model - Case 4



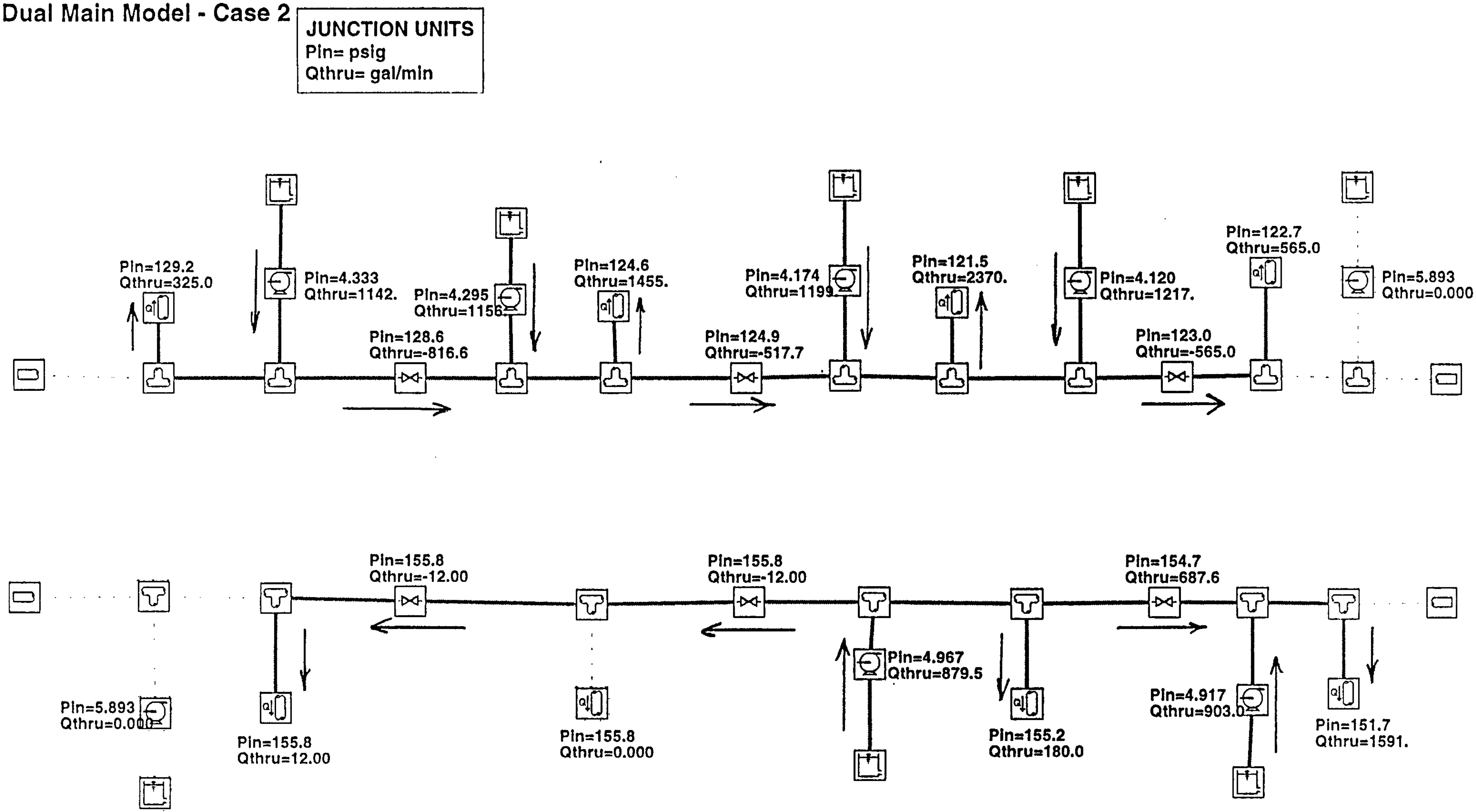
Offset Loop Model - Case 5, All Valves Open



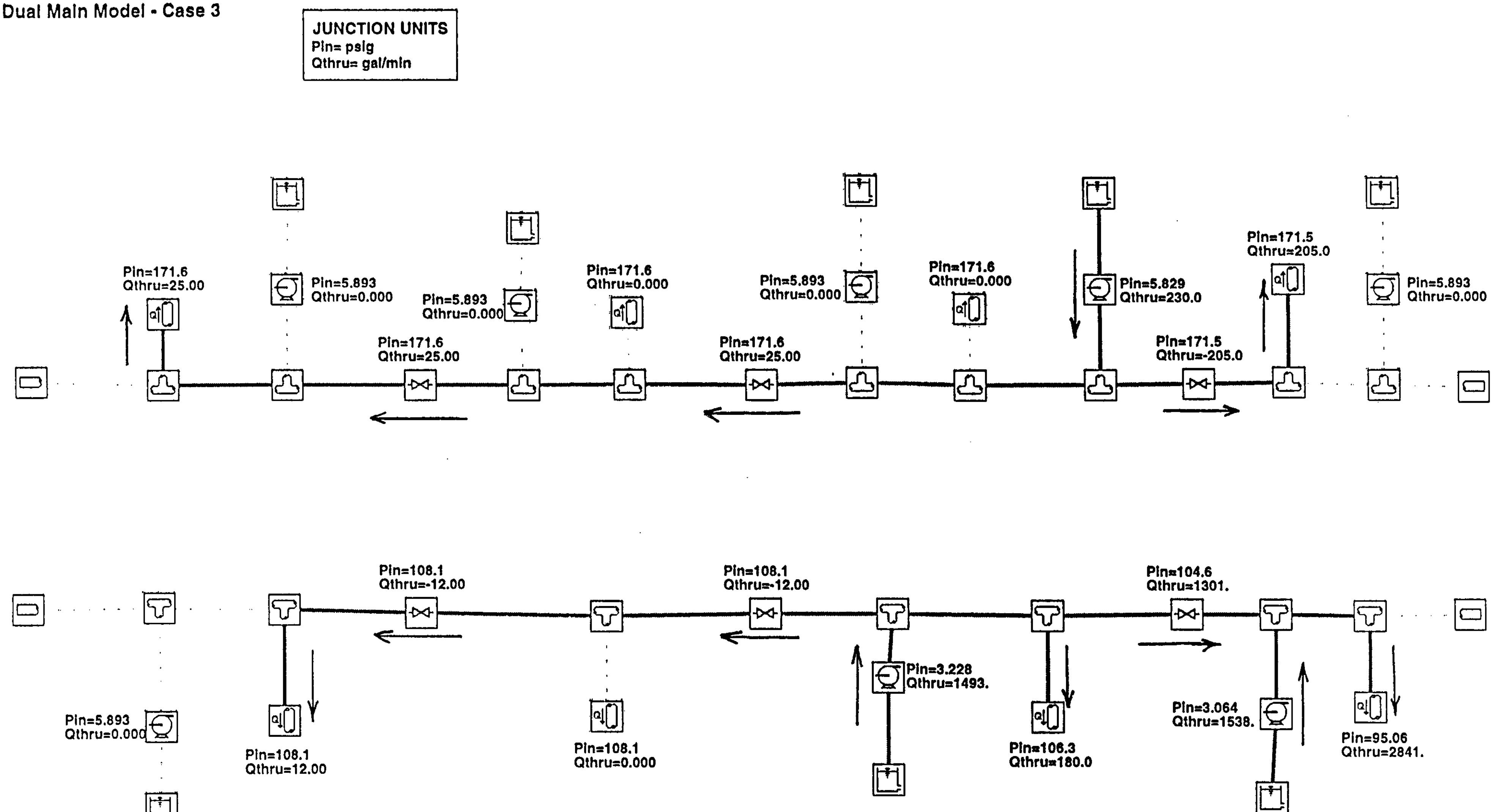
Offset Loop Model - Case 6, All Valves Open



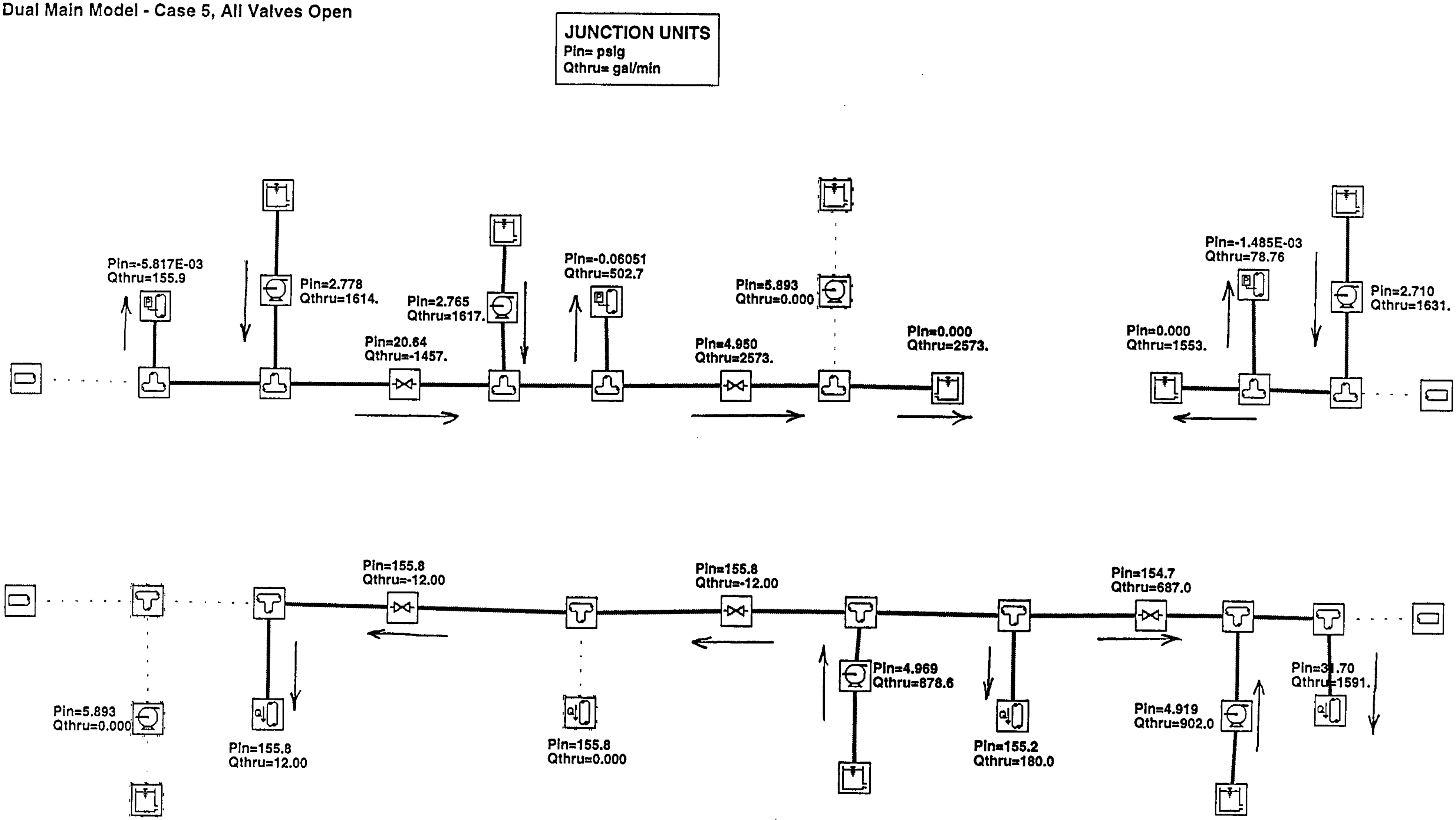
Dual Main Model - Case 2



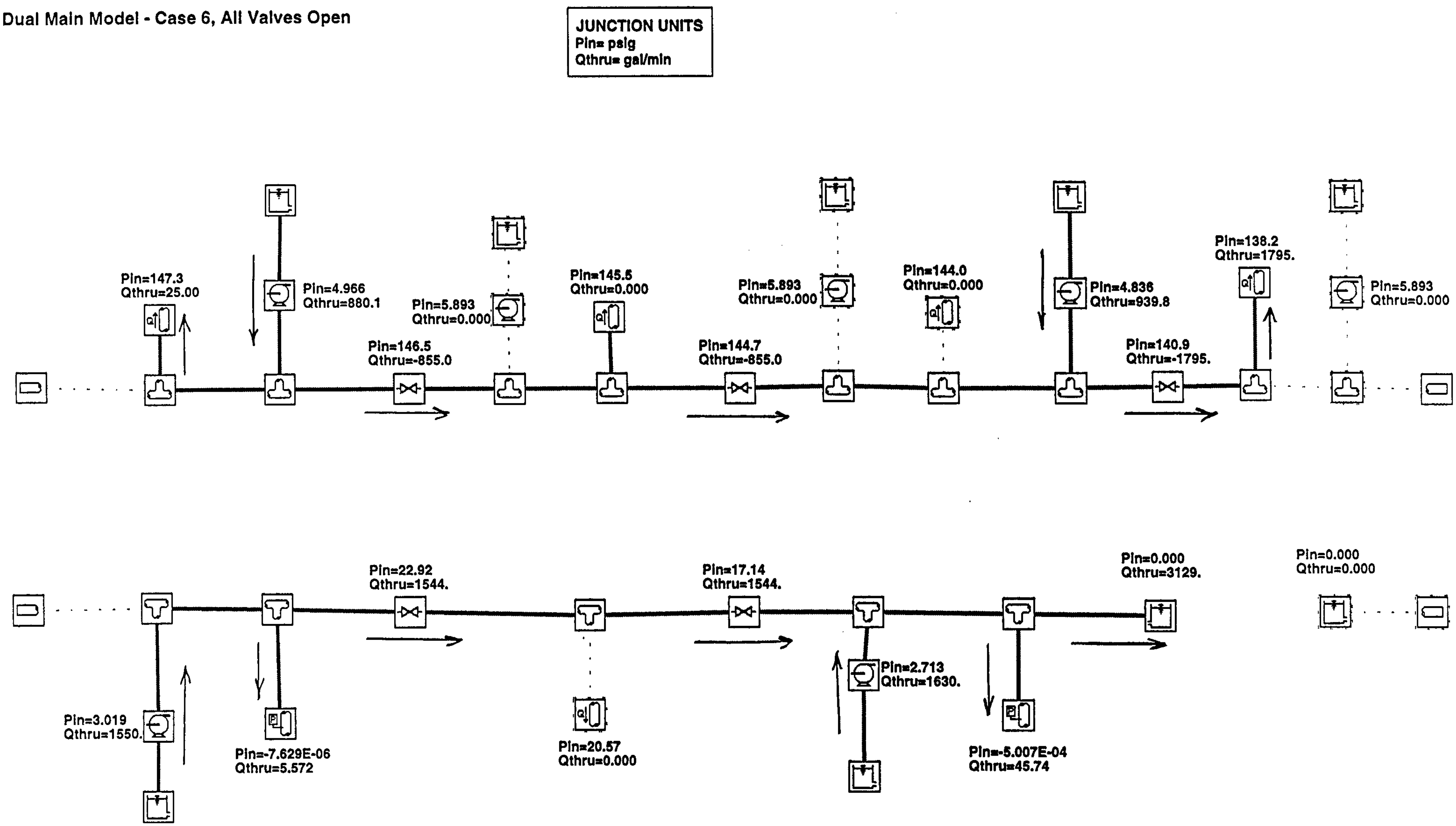
Dual Main Model - Case 3



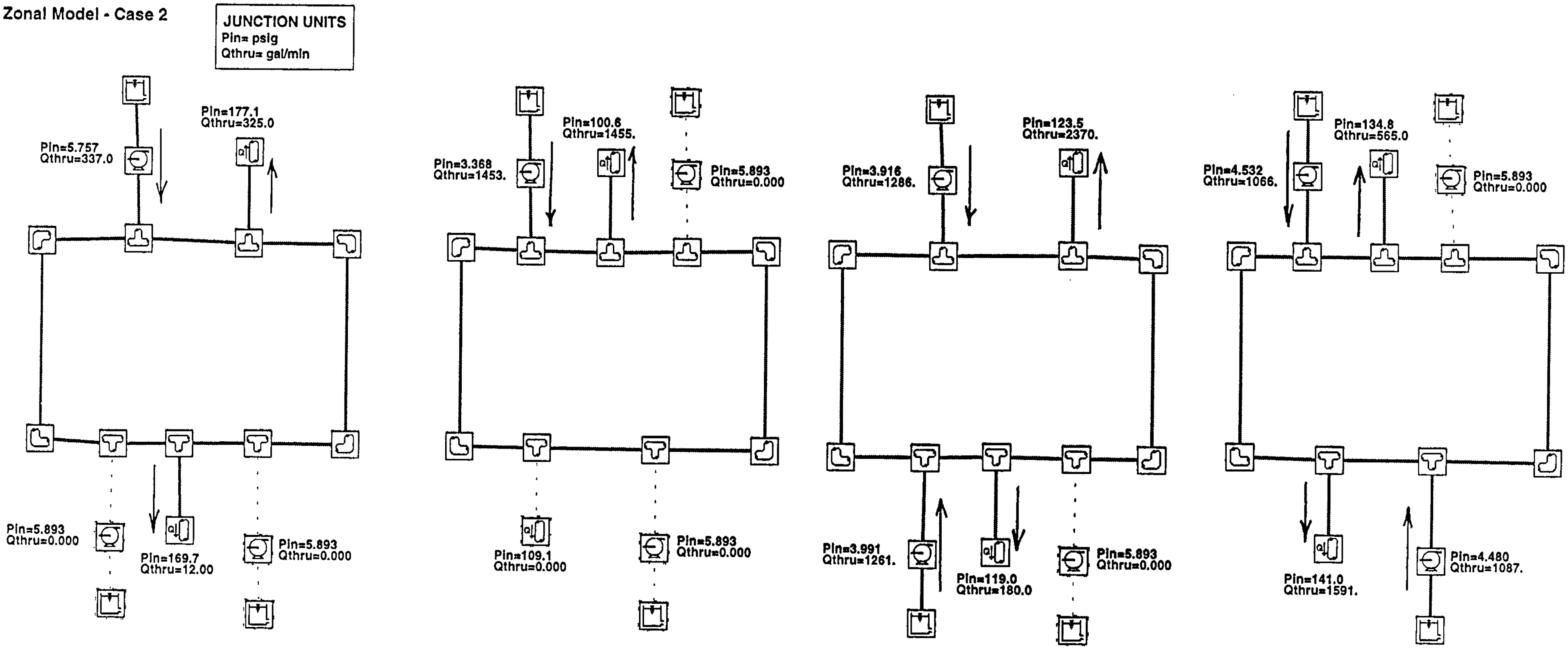
Dual Main Model - Case 5, All Valves Open

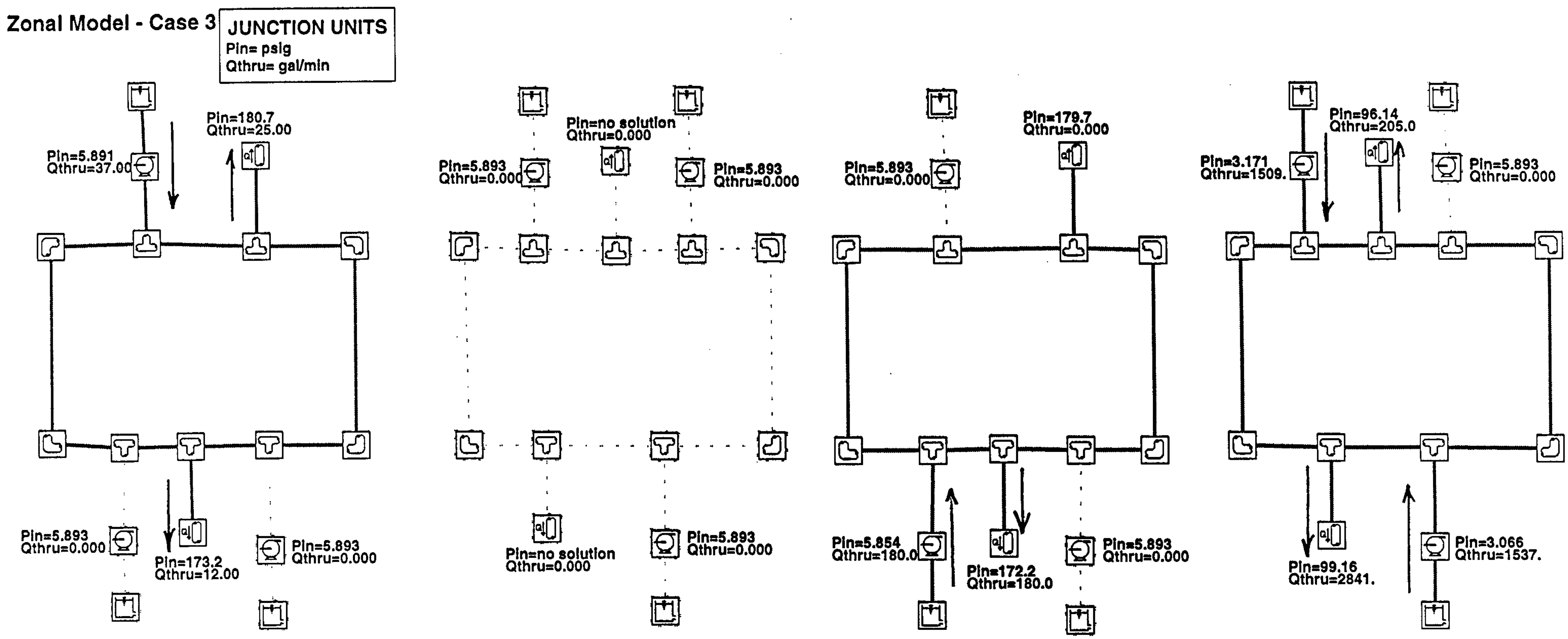


Dual Main Model - Case 6, All Valves Open

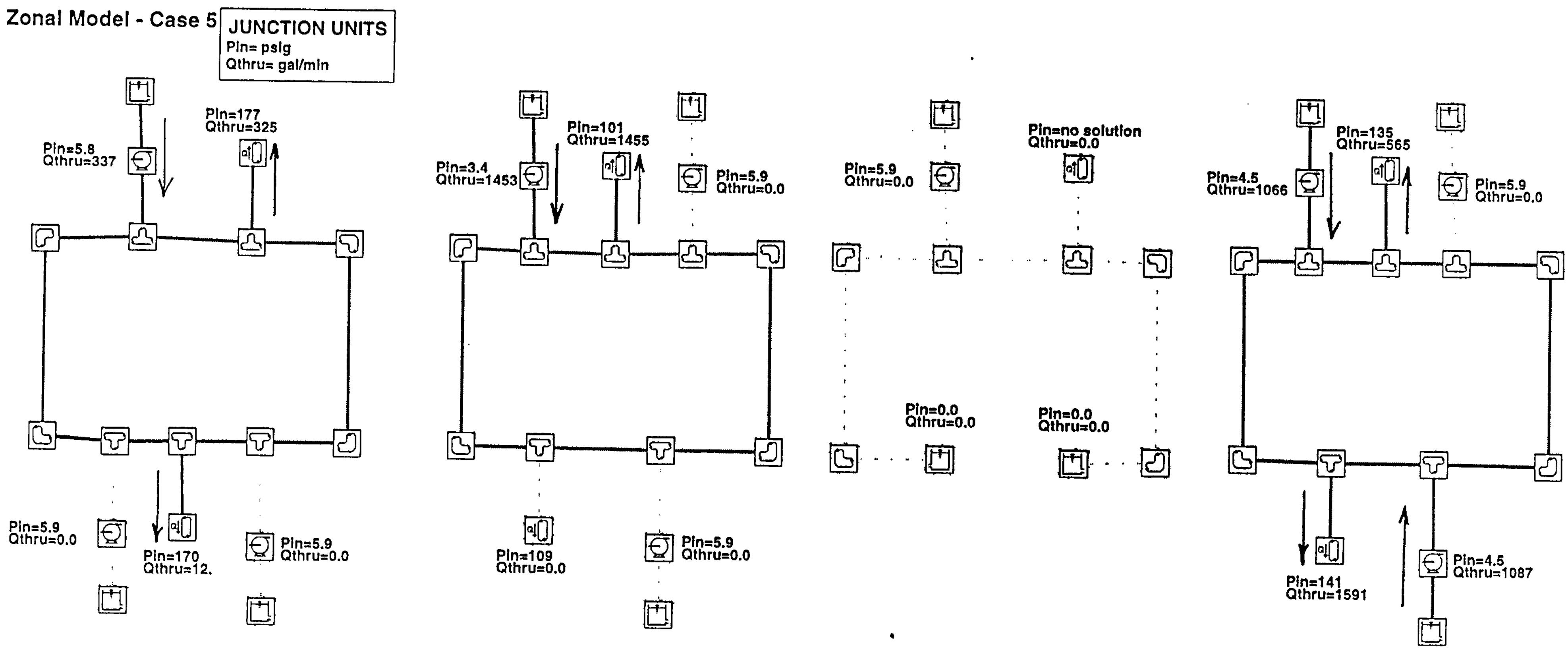


Zonal Model - Case 2





Zonal Model - Case 3
JUNCTION UNITS
Pin= psig
Qthru= gal/min
Pin=5.891
Qthru=37.00
Pin=180.7
Qthru=25.00
Pin=5.893
Qthru=0.000
Pin=173.2
Qthru=12.00
Pin=5.893
Qthru=0.000
Pin=5.893
Qthru=0.000
Pin=no solution
Qthru=0.000
Pin=5.893
Qthru=0.000
Pin=no solution
Qthru=0.000
Pin=5.893
Qthru=0.000
Pin=5.893
Qthru=0.000
Pin=179.7
Qthru=0.000
Pin=5.854
Qthru=180.0
Pin=172.2
Qthru=180.0
Pin=5.893
Qthru=0.000
Pin=3.171
Qthru=1509.
Pin=96.14
Qthru=205.0
Pin=5.893
Qthru=0.000
Pin=99.16
Qthru=2841.
Pin=3.066
Qthru=1537.



Zonal Model - Case 5
JUNCTION UNITS
Pln= psig
Qthru= gal/min
Pln=5.8
Qthru=337
Pln=177
Qthru=325
Pln=5.9
Qthru=0.0
Pln=170
Qthru=12.
Pln=5.9
Qthru=0.0
Pln=3.4
Qthru=1453
Pln=101
Qthru=1455
Pln=5.9
Qthru=0.0
Pln=109
Qthru=0.0
Pln=5.9
Qthru=0.0
Pln=5.9
Qthru=0.0
Pln=no solution
Qthru=0.0
Pln=0.0
Qthru=0.0
Pln=0.0
Qthru=0.0
Pln=4.5
Qthru=1066
Pln=135
Qthru=565
Pln=5.9
Qthru=0.0
Pln=141
Qthru=1591
Pln=4.5
Qthru=1087

Zonal Model - Case 6